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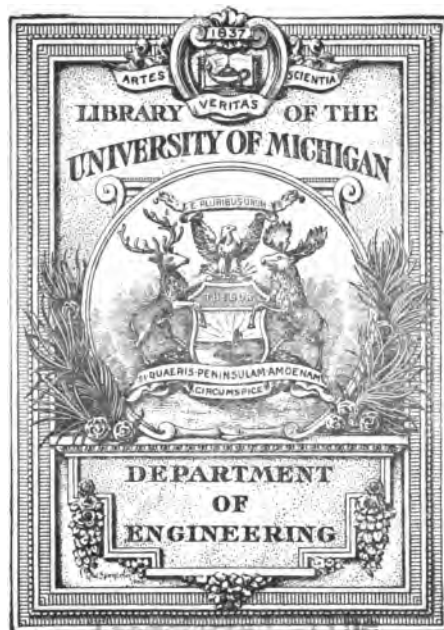
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NAVAL PROFESSIONAL PAPERS
No. 13

MAGNETISM:

ITS PRINCIPLES AND APPLICATION TO
SHIPS AND COMPASSES

BUREAU OF NAVIGATION
NAVY DEPARTMENT



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MAGNETISM:

ITS GENERAL PRINCIPLES

AND SPECIAL APPLICATION TO SHIPS AND COMPASSES.

BUREAU OF NAVIGATION,
NAVY DEPARTMENT.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1883.

PREFACE.

As the MAGNETISM of the Mariner's Compass is its distinctive feature, a knowledge of the principles of magnetic science is essential to an intelligent and just understanding of the behavior of the compass when placed in the midst of a magnetic body—an iron ship, which it is to guide, and whose safety is greatly dependent upon it.

In order to afford to the officers of the Service, in a readable form, the requisite information on the subject, this paper has been compiled.

Part I deals with the general principles and phenomena of the science, that have been discovered by the most eminent investigators. It is taken from a work by Sir W. Snow Harris, F. R. S.

Part II treats the subject as specially appertaining to compasses and ships, and is from the writings of the Rev. W. Scoresby, D. D., F. R. S.

Part III describes the method of compensating compasses by means of magnets, and is at once a clear direction for performing the operation and a concise exposition of the varied forms of the force acting upon the compass. It is taken from a work on navigation by Capt. S. T. S. Lecky, R. N. R.

Some *apparent* repetition occurs in the three parts; but the treatment by the different authors of the same point is supplemental one of another—light thrown upon it from a new standpoint—rather than real redundancy.

It should be understood that the magnetic instruments described, bear the same relation to those in actual use to-day, that lecture models do to the refined and delicate instruments of the best makers—they merely illustrate the principle involved; to do more would not be suitable to this paper.

BUREAU OF NAVIGATION, NAVY DEPARTMENT,
Washington, December, 1883.

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MAGNETISM.

PART I.

MAGNETISM.

CHAPTER I.

THE NATURAL MAGNET.

The natural magnet, or lodestone—Its general history—Nature and properties—Communicative power—Directive power—Terms by which the magnet has been characterized by various nations—Magnetic poles or points of greatest attraction—The armed magnet—Reciprocal polar attractions and repulsions—Views of the ancient philosophers on the nature of magnetic attraction—Modern views.

1. The earliest scientific records notice the operations of a subtle natural agency, peculiar in many respects to bodies containing iron, and acting more especially on iron and steel. By this agency, ferruginous particles are drawn together, and frequently remain suspended one from the other in opposition to the force of gravity.

Notices of such phenomena are found in very ancient manuscripts, especially in those of China, and also in the writings of the Greek and Roman philosophers—Thales, Pythagoras, Plato, Aristotle, Lucretius, Cicero, Pliny, and several others.

2. The existence of this subtle agency was first observed as a property of a mineral substance of a grayish or reddish-black color. The Greeks obtained it from the province of Magnesia, in Lydia, and termed it the *magnesian stone*, also *μάγνης* (magnes), from whence the modern terms *magnet* and *magnetism*, the one designating the mineral substance itself, the other the peculiar agency supposed to reside in it. Hence also the term *magnetic attraction*, employed to characterize the power or force in operation.

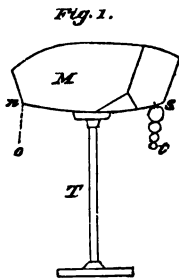
3. The magnesian stone, or *native magnet*, abounds in various parts of the earth, especially in iron mines, where it is found massive, frequently crystallized, and occasionally in beds of considerable thickness. Its constituents are, for the most part, oxygen and iron under the form of two oxides, the black and red. In 100 parts we have about 73 parts iron and 27 oxygen; it has been termed *magnetic iron ore*. Its color varies from a reddish-black to a deep gray. Native magnets from Arabia, China, and Bengal are commonly of a reddish color, and are powerfully attractive. Those found in Germany and England have the color of unwrought iron; those from Macedonia are more black and dull.

The specific gravity of magnetic iron ore is about four and a half times that of water, and affords, when worked, excellent bar iron.

The native magnet is sometimes found in the form of small grains,

constituting what has been termed *magnetic iron sand*. Magnetic sand abounds in the Isle of Skye, and in Fifeshire, in Scotland. We find also in the iron mines of Norway a thick black earthy powder possessing magnetic properties.

4. This remarkable substance has not only the power of drawing apparently towards itself small particles of iron, and of holding suspended from various parts of its surface light rings and other small masses of iron or steel, but, as the ancients observed, it has also the important property of communicating or propagating, as it were, its own attractive power through a series of such rings or masses, so as to cause them to hang one on another in a sort of linked chain.



EXPERIMENT 1. In the annexed Fig. 1, let the mass M be an irregular block of magnetic iron ore, mounted on any convenient support T; there will be found certain points, *n s*, on its surface so powerfully attractive as to sustain a series of short needles of iron *n o*, or a series of soft steel rings *s t*, which may be suspended successively one from the other solely by the force imparted to them from the magnet M.

5. In the celebrated philosophical poem, "*De Rerum Natura*," by the Roman poet Lucretius, who flourished about sixty years before the Christian era, we find the magnet, together with these illustrations of its power, very beautifully treated. Dr. Busby, in his translation of this poem, thus renders the passage:

Now, chief of all, the magnet's power I sing,
And from what laws the attractive functions spring;
The magnet's name the observing Grecians drew
From the magnetic region where it grew;
Its viewless potent virtues men surprise,
Its strange effects they view with wondering eyes,
When, without aid of hinges, links, or springs,
A pendent chain we hold of steely rings
Dropt from the stone—the stone the binding source—
Ring cleaves to ring, and owns magnetic force:
Those held superior, those below maintain,
Circle 'neath circle downward draws in vain,
Whilst free in air disports the oscillating chain.

6. The attractive force of the magnet, as shown in this experiment, is found to reside principally in opposite points of its surface. These points have been termed *poles*, from another wondrous property of the magnet said to have been known to the inhabitants of China from time immemorial, but with which the philosophers of Greece and Rome were certainly not acquainted.

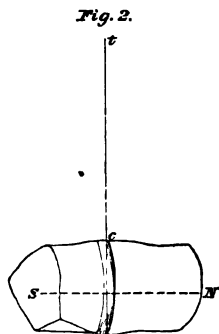
If the magnet be suspended by a delicate silk line from some point between the surfaces of attraction, so as to admit of its turning freely on that point, the mass will rest only in one position: this position will

be such as to place its poles either in the line of the meridian, or very near it; one of the surfaces of the mass will have turned towards the north, and the opposite surface towards the south, and, if drawn aside from this position, will continue to vibrate backward and forward until it again rests in the same position.

In some very irregular and peculiar pieces of magnetic iron ore several such poles have been observed, but they are always in opposite points of the mass; the native magnet, however, has generally two poles only.

EXPERIMENT 2.—Immerse a piece of magnetic iron ore in fine iron or steel filings; the particles will be attracted, and will collect principally in separate and aggregated knots on certain opposite points of its surface.

EXPERIMENT 3.—Having ascertained the position of the poles or points of greatest attraction, as at N S, Fig. 2, trim the specimen in the direction of their axis or line N S, supposed to traverse the mass from one point to the other, so as to give it a somewhat oblong regular form, as represented in the figure. Suspend the mass by a fine thread of silk, *c t*, in some point, *c*, intermediate and as central as possible between the poles N S; the mass will turn and rest in such a position as will place the extremities of the axis N S either in the direction of the meridian, or in a line varying from it by a given angular quantity either east or west, depending on the particular locality of the experiment, so that one of the poles, N, will have turned towards the north, and the opposite pole, S, towards the south, from which circumstance N has been called the *north*, and S the *south* pole of the magnet.



7. The property by which the magnet is caused to assume this particular position has been called magnetic *polarity* or *directive power*, and when the magnet is free to move into this position it is said to *traverse*.

A plane perpendicular to the horizon and passing through N S, the poles of the magnet whilst in their directive position, is called the *plane of the magnetic meridian*. The line N S has been termed the *direction of the magnetic meridian*. The angle made between the line N S, or direction of the magnetic meridian, and the line of the true meridian of the place in which the magnet is suspended, has been termed the *variation* or *declination* of the magnet, or simply the *magnetic declination*.

8. The native magnet appears to have been known in almost every country, and at remote periods. The Jews were evidently acquainted with it. In the Talmud it is termed "achzhab'th," the stone which attracts, and in their ancient prayers it has the European name magnēs. The term employed in different languages to designate the magnet is, as may be readily imagined, commonly based upon its supposed "love

of iron." Thus, in the Chinese, we have the term "thsu-chy," or love-stone, also "ly-thy-chy," the stone which suatches up iron. In the Siamese we have the term "me-lek," that which attracts iron. In the Sanscrit the magnet is termed "ayaskānta," loving toward iron. Euripides terms it "lapis Herculanæus," the Herculean stone, from its power over iron. Amongst the European languages we find in the French "l'aimant," or the loving-stone; in the Spanish "iman." In Hungarian we have again the term "magnet kö," the love-stone; and so of a variety of others.

In several remarkable instances the magnet has been characterized by its directive property (7): thus, in the Chinese we have the term "tchu-chy," the directing stone. In Tonkin we have the term "d'ân-amtchûm," the stone which shows the *south*. In Swedish we have "segel-sten," the seeing-stone. In Icelandic "leiderstein," the leading stone, after the Saxon of "lædan," to *lead*, from whence the English name "loadstone," or "lodestone," and by which term the magnet is commonly known in England. In a similar way we derive the term "lodestar," or guiding star, as applied to the star of the pole; also the term *lode*, as applied to the leading vein in mining.

In a few instances the magnet has been named after the great hardness of its structure. The Greeks subsequently termed the magnet *καλαμίτας*, from whence the word "kalamit" and *calamita* used by the early French writers, and employed by the Italians and by some other European nations at the present day. In the Hebrew also we find occasionally the term "kalmithath" and "khalamish," signifying hard, callous, rocky. In the Roman we have the word "adamas," after the Greek *ἀδάμας*, signifying unmanageable.

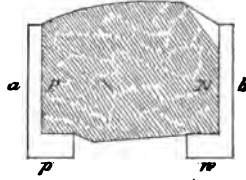
9. The attractive force of the lodestone or natural magnet cannot generally be considered as of any great amount. Native magnets in their rude state will seldom lift their own weight, and with some rare exceptions their power is limited to a few pounds. The smallest magnets appear to have the greatest proportionate power. Sir Isaac Newton is said to have possessed a small magnet set in a ring, the weight of which was only 3 grains, but which supported by its attractive power on iron 700 grains; such instances, however, are by no means common. A native magnet presented by the Emperor of China to King John V of Portugal, the weight of which was about 38 pounds, was found in February, 1781, to sustain above 200 pounds, or above five times its own weight.

10. The effective power of the lodestone may be considerably improved by means of what is termed an *armature*, which consists of small pieces of very soft iron applied to the opposite polar surfaces of the stone, and projecting a little below it on each side. The attractive force is thus transmitted to the small projecting or artificial poles of iron (4): this is found not only to augment the power, but also to enable the experi-

mentalist to bring both the poles to bear upon any given mass at the same instant.

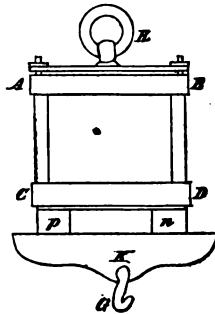
In arming a lodestone in this way, care must be taken to select a piece of magnetic ore iron having two poles (6), and possessing some considerable power. The opposite faces P N, Fig. 3, in which the poles reside, should be squared off by a lapidary's wheel, and made smooth and regular, and in some cases it may be desirable to trim the specimen and give a regular form to the whole block, keeping the distance of the poles P N or axis N S, Fig. 2, as great as possible.*

Fig. 3.



The pieces intended for the armature should be made of very soft iron, and each formed with a vertical face about one-eighth to one-fourth of an inch thick, with a projecting solid foot below, as at *a p* and *b n*, Fig. 3; the vertical face being closely applied to the polar surfaces, and the mass allowed to rest on the projecting feet *p n*, forming the artificial poles. Things being thus arranged, the whole is bound firmly together by a cap of silver or brass, or by plain metallic bands, as represented in A B and C D, Fig. 4. A ring R is usually fixed in the upper part of the cap for the convenience of raising the whole mass, and a transverse piece of soft iron K, termed a keeper or lifter, furnished with a central hook G, is placed across the artificial poles *p n*, so as to unite them. This keeper is found to preserve and increase the attractive force of the poles, especially if the magnet be suspended by its upper ring R, and weights be attached to the hook G, and by which its power may be roughly estimated.

Fig. 4.



If the armed magnet be thus suspended, and a small scale-pan attached to the keeper K, an additional weight may be added daily for a considerable time; the lodestone thus armed may be caused to sustain from twenty to thirty times its own weight.

When an armed lodestone is employed for particular experimental inquiries or other purposes, the keeper K may be removed, but it should be replaced when the magnet is not in use.

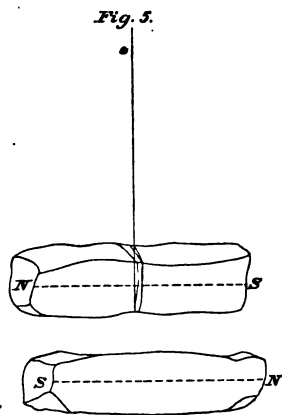
11. Although the attraction of the magnet for iron may be considered as its most general and characteristic property, yet this property has not been found so universal as to be without very remarkable exceptions; the exceptions being such as to involve what at first appears a totally opposite and different kind of power. Pliny, in the thirty-sixth book of his Natural History, has an obscure allusion to such a power. There

* The native magnet being of a callous and close texture, sufficiently hard to afford sparks when struck against steel, is difficult to work with common tools. It may, however, be trimmed into form by means of a lapidary's wheel, or other wheels employed in cutting and grinding glass.

is, he says, "a kind of stone in Ethiopia, which will not abide iron, but repulses and driveth iron away."* Marcellus, an empirical physician, who flourished under the Emperor Theodosius, about the year 400 of our era, alludes to the magnet as the attractor and repulsor of iron.

It is, however, very doubtful whether the ancients were fully acquainted with the properties of magnetic repulsion, such as now observed. Lucretius, who was certainly well acquainted with the history of science up to his time, is quite silent upon this subject. The discovery, therefore, of the repulsive power of the magnet is, in all probability, of very modern date.

If we suspend a magnet by a fine silk fiber over another magnet, or near another magnet also suspended, the poles of these magnets will arrange themselves in such a way as to bring the opposite poles together; the similar poles are found so powerfully and reciprocally repulsive, as not to allow the masses to rest with their similar poles in juxtaposition.



EXPERIMENT 4.—Procure two small masses of magnetic iron ore, and having determined the position of the poles (6), prepare the pieces as before described (6), and suspend one over the other, as in the annexed Fig. 5. The north poles N N will be found to arrange themselves immediately opposite the south poles S S, and so decidedly that the suspended magnet N S, will not rest in any other position.

12. We perceive, then, by this experiment that a repellent magnetic force is attendant on magnetic polarity, and that consequently any mass of iron having fixed polarity (7) would be repulsed by the magnet whenever the like poles were opposed to each other. Now the polarity of the lodestone is altogether dependent on the iron it contains; and we should therefore expect to find common iron possessing, in certain instances, similar properties to those of the magnet. Such cases would be attended by the development of a new and opposite force, not observed in the ordinary operations of the magnet on ferruginous matter. It is well known that pieces of common iron, which have been for a great length of time in one fixed position, or underground, acquire considerable polarity—in fact, become magnets; this very frequently happens with old turret vane-spindles, and the old rusty bars of abbey windows. In the "Memoirs of the Academy of Sciences" for 1731, we find an account of a large bell at Marseilles having an axis of iron; this axis rested on stone blocks, and threw off from time to time great quantities of rust, which, mixing with the particles of stone and the oil used to facilitate the motion, became conglomerated

* "Alius rursus in eadem Ethiopia non procul mons gignit lapidem theamedem, qui ferrum omne abigit respuitque."

into a hardened mass; this mass had all the properties of the native magnet. The bell is supposed to have been in the same position for 400 years.

This curious fact not only serves to elucidate the early observations of the magnet's repulsion for iron, but it throws further light on the probable source of the polarity of the magnet itself.

13. The views of the ancient philosophers respecting the immediate source of the power of the magnet were such as, on a first acquaintance with the phenomena, might have been anticipated. Directing their attention to occult causes, they were driven to assume the existence of a peculiar essence or effluvium, which, being emitted by the magnet, dragged the iron, as it were, into its embrace. Lucretius advances a step further upon this crude idea, and supposes that the magnetic effluvium drives the air out of the space existing between the magnet and a piece of steel or iron, and, by thus producing a vacuum, causes the iron to be pressed towards the magnet. In his poem we find the following lines as translated by Busby:

Soon shall we trace by what mysterious laws,
What secret energy, what latent cause,
Steel, the strong magnet, actuates and draws.
First, then, my loved illustrious Memnon, know,
Ceaseless effluvia from the magnet flow,—
Effluvia, whose superior powers expel
The air that lies between the stone and steel.
A vacuum formed, the steely atoms fly
In a link'd train, and all the void supply;
While the whole ring to which the train is join'd
The influence owns, and follows close behind.

Thales, the celebrated philosopher of Miletus, conceived the magnet to be endowed with a sort of immaterial spirit, and to possess a species of animation.

14. Leaving for the present, however, all such metaphysical speculations, it will be sufficient to recognize the important fact, that whatever be the hidden cause of magnetic phenomena, it may with safety be inferred, from the attractions and repulsions of similar and dissimilar poles just described (11), that the direct practical consequence of magnetic polarity is the development of two dissimilar and distinct forces, repulsive of themselves, but attractive of each other. It is with these two forces, and the laws of their action, that the experimentalist and mathematician is more immediately concerned; they have been accordingly considered as positive and negative forces, and have been characterized by the positive and negative signs. These forces have been also termed north and south polarities, or magnetism, as expressive of their mutual relations to the directive property of the magnet. The following simple formula expresses concisely the fundamental law of their reciprocal action: "Similar polarities repel, opposite polarities attract each other."

15. From whatever source the forces may arise, that would in no way

affect their existence as mechanical qualities. In looking through the operations of other hidden principles of nature, we find in all of them what may be considered as opposite or antagonistic qualities. Thus we have light and darkness, heat and cold, gravity and levity, action and reaction, &c. Now, although it be proved that no positive principles, such as darkness, cold, levity, &c., have existence, yet, taken as the negatives of light, heat, gravity, &c., we could, if it were requisite, represent and employ darkness, cold, levity, &c., as so many antagonistic forces. If I mix a certain quantity of hot water with a certain quantity of ice, I may, in a certain sense, be said to mix heat and cold together; and the resulting temperature would be either a neutral temperature, as referred to a given standard, or it would be in excess or defect of such a standard, and might be faithfully characterized either by zero or by the positive or negative signs, to denote the excess or deficiency in relation to this standard. In the present imperfect state of our knowledge of the cause of electrical and magnetic forces, it is at least useful and convenient to consider these forces under this form, with a view of better representing to the mind the laws of magnetic action, and linking into an intelligible chain the several phenomena presented to us.

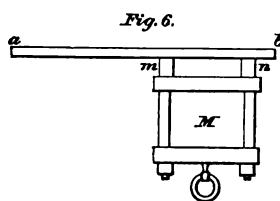
CHAPTER II.

THE ARTIFICIAL MAGNET.

The artificial magnet—How produced—Various forms and methods of magnetizing—Properties of a magnetic bar—It assumes a definite position of direction and inclination—Its force variable in different points of its length—Magnetic center, axis, and poles—Attraction and repulsion of the opposite polar forces—Lines of magnetic force—Reciprocal action of magnetic bars on each other—Magnetic induction or influence—Reactive force of iron on magnets.

16. The communicative property of the lodestone (4) may be considered as the great source of the advances, and of many of the grand modern discoveries achieved in this interesting department of science; for although the attractive property communicated to soft iron or steel by contact with the lodestone (Fig. 1) commonly vanishes as soon as the iron is removed from the magnetic pole, yet in many remarkable instances the attractive power, together with all the properties of the original magnet, remain, and we obtain what has been termed an *artificial magnet*.

EXPERIMENT 5.—Procure a small bar of steel about 8 inches in length, one-fourth of an inch wide, and one-eighth of an inch thick, or a piece of common steel wire of about the same length and from one-eighth to one-fourth of an inch in diameter. Let the steel be well hardened and tempered by plunging it at a cherry-red heat into cold water; when cold and polished, apply each extremity in succession to the opposite poles of an armed magnet, Fig. 3, first touching with gentle friction one extremity of the bar, or one of the poles



and the opposite extremity on the other pole, or, which is better, draw the bar $a b$, Fig. 6, a few times, in the direction of its length, across the two poles $m n$ of the magnet M , as represented in the figure, and in such a way as not to pass either extremity, $a b$, beyond or off the opposite poles $m n$; finally, bring the bar $a b$ so as to rest with its extremity $a b$ equally distant from each pole $m n$; that is to say, bring the poles $m n$ at the center of the bar, or as nearly as may be. In this position remove the bar from the poles. The bar will now be found attractive of particles of iron, common steel needles, and other ferruginous matter; when suspended it will arrange itself in the direction of the magnetic meridian and will, in fact, have all the properties of the lodestone, including the important property of imparting or exciting a magnetic condition in tempered steel.

EXPERIMENT 6.—Take a small bar of steel which has been rendered magnetic by the process just described (Experiment 5), apply it with slight friction to a piece of hard steel wire or a similar bar, and in such way that the opposite extremities of each bar may have contact attended by a slight degree of friction; this second bar or wire will be found also to have acquired a similar magnetic condition to the first; and this process may be continued from the second to a third wire of steel, and so on without limit.

The propagation of magnetism from one bar of steel to another, as illustrated in this experiment, enables the experimentalist to obtain artificial magnets to any number; and since the form and magnitude of the steel has not been found to interfere with the generality of the result, we are further enabled to obtain magnets of any required figure or magnitude.

17. It is to be especially observed that the polarities (14) excited in the opposite portions of a steel bar by this artificial process of magnetizing (16) are the reverse of those of the magnetic poles to which these portions have been applied. Thus in Experiment 5, Fig. 6, if the extremity b of the steel $a b$ rest on the north or positive pole n of the magnet M , the polarity induced in that extremity b will be a south or negative polarity. Reciprocally, if the extremity a be brought to rest on the negative or south pole m , then the polarity induced in that point of the steel will be a positive or north polarity.

This result may be conceived to depend upon the general principle already explained (14), viz, that the north magnetism of the pole n of the magnet repels the similar or north magnetism of the bar, and attracts the south, and reciprocally the south magnetism of the pole m repels the similar magnetism of the bar, and attracts the north; hence the two positive and negative elements (14) resident in the bar have become disunited, and caused to appear as two separate and distinct forces. Hence it has been found desirable for practical purposes to mark one extremity of an artificial magnet with a small file-cut, carried round the bar; the marked end is generally that extremity which points north

when the magnet is suspended. This means of distinguishing the two poles is found of great importance in practical magnetism.

18. Magnetized steel was in all probability first obtained in the way just described (16), as may be inferred from several terms used by the Chinese and Indian nations to designate the magnet. One of these, used by the Chinese and Japanese, refers to the magnet as the "stone for rubbing the needle"; others call it the "stone for the steel needle." The native magnet, however, is not the only source of magnetism in steel; it is now found that a magnetic condition may be excited in hard steel by various mechanical processes, such as filing, hammering, drilling, and the like; also by changes of temperature, as in the heating and cooling of iron; likewise by mere position alone; finally, by voltaic or common electricity.

19. We have now arrived at a complete notion of an artificial magnet, which, as we see, consists of a mass of hard steel possessing all the properties of the lodestone, and which have been imparted to it by artificial means.

Artificial magnets, as just observed, may be of any required form, or

Fig. 7.

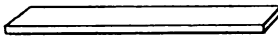


Fig. 8.



Fig. 9.

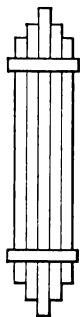
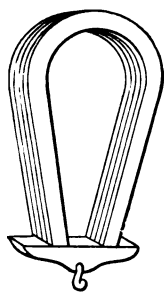


Fig. 10.



of almost any dimensions, according to the particular views of the experimentalist: for general purposes they are limited to straight bars, such as presented in Fig. 7, or otherwise to bars bent into a curvilinear form, resembling a horseshoe, as in Fig. 8; the branches cp and cn being longer, and the extremities pn nearer than in the common horseshoe. Many such bars, either straight or curved, form, when combined, what is termed a *compound magnet*, such, for example, as that represented in Figs. 9 and 10. The combination of several compound magnets with projecting armatures (10) constitutes a *magnetic battery* or *machine*. The dimensions well adapted to magnetic bars, either straight or curved, are such as to give the breadth about one-fourteenth or one-fifteenth of the length, and the thickness something less or not exceeding one-half of the breadth.

20. Although the simple method of magnetizing we have just described (16, Experiment 5) is sufficient for small bars, plates, or cylinders of steel, yet it is not equally applicable when required for the production of a high degree of power in artificial magnets of considerable magnitude. To obtain this, several methods of magnetizing have been proposed; it may, however, be at present sufficient to describe the following—the best perhaps of any for general practical purposes.

Let it be required, for example, to magnetize two straight bars of highly-tempered steel. Place the bars $p s$, $p' s'$, Fig. 11, on a flat board between two pieces of soft iron, $p s'$, $p' s$, about 6 inches in length, and of the same breadth and depth as the bars, and in such a way that the opposite marked extremities, $p p'$, may be in opposite angles of the parallelogram $p p'$. This arrangement being made, and the parallelogram secured in its position, apply an armed magnet, or, what is better, a combination of magnetical horseshoe bars M , to one end, s , of either of the bars $p s$, taking care, on the principle explained (16), to place the compound magnet M on the bars in such a way that its marked pole will rest next the unmarked extremity, s , of the bar, or conversely if placed on the marked extremity, p , of one of the bars; then the opposite or unmarked pole of the compound magnet M may rest next the marked pole p . Things being thus arranged, continue to slide the magnet upon the bar, carrying it completely round the whole parallelogram in one direction, $s p$, $s' p'$, and stopping finally in the center, c , of one of the bars. Repeat this process on each face of the bars, and a very high degree of force will be found to have been produced; the whole parallelogram will hang together, and each bar, on separating the keepers, $p s'$, $s p'$, will have acquired a high amount of permanent magnetism.

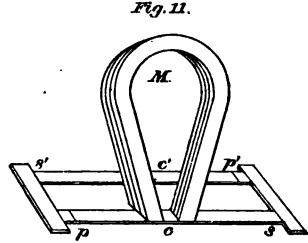


Fig. 11.

To magnetize a bar of tempered steel, curved into the horseshoe form fix the bar, Fig. 12, on a flat board, with its extremities, $p s$, against a straight piece of soft iron, $p s$, of the same thickness and width as the bar. Having secured the whole in this position, place a compound magnet, M , or an armed native magnet, on one of the extremities, s , of the curved bar, taking care c that the opposite or marked and unmarked ends are in contact with each other. Continue as before to glide the magnet M several times round the whole series, and in the same direction, $s c p$, finally stopping in the center, c . Repeat this process on each face of the bar, when a high degree of power will have become developed; so much so that the iron or keeper $p s$ cannot be directly pulled away without considerable force, and in some instances cannot be conveniently removed, except by sliding it off.

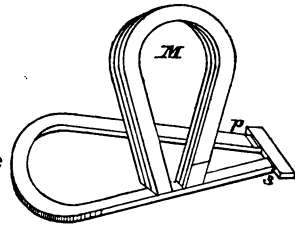


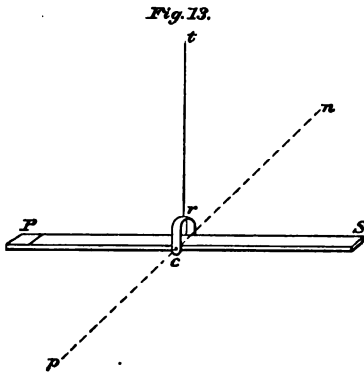
Fig. 12.

In order to preserve effectually the magnetism thus excited in bars of steel, it is requisite, when not in use, to keep their opposite poles united by means of pieces of soft iron; that is, in the same way precisely as in the process of magnetizing shown in Figs. 11 and 12.

21. Properties of a magnetic bar.—If a bar of tempered steel be carefully prepared and poised upon a central point so as to be indifferent as to

position, and further, be so balanced and suspended as to be at liberty to move in a horizontal plane, then, on being rendered magnetic (16), it will be no longer indifferent as to position, but will gradually settle in a plane either passing immediately through the meridian of the place or differing from it by a given angular quantity; if turned aside from this direction, and again set free, it will continue to oscillate across the meridian backwards and forwards, until it again rests in the same position, as in the case of the native magnet (6). If the bar be also at liberty to move in a vertical plane, then, whilst turning into this meridional plane, it will at the same time incline or dip one of its extremities below the horizontal line, which in these latitudes amounts to an angle of nearly 70° . The extremity which thus dips is, in latitude north of the equator, turned towards the north pole of the earth, and in latitudes south of the equator towards the south pole of the earth. The inclination increases as we proceed north or south from a certain great circle of the sphere traversing the equatorial parts of our globe, and in which the inclination is nothing.

EXPERIMENT 7.—Take a perfectly straight and even bar of steel, P



S, Fig. 13, sufficiently hard to retain a magnetic state. It may be 7 inches long, one-eighth of an inch wide, and one-tenth of an inch thick. Drill a clean hole through the center of the wide surface, and then pass an extremely fine drill also through the center transversely to this hole, across the thickness of the bar, edgewise, and so accurately as to pass through the center of gravity of the mass, or as nearly as possible; proceed now to complete the equilibrium of

the bar upon a fine needle as an axis, and in such a way as to render it indifferent as to position in a vertical plane, or nearly so, and that whether it be placed with one or the other face uppermost. Let the bar be now magnetized (16), and then mounted on its central axis; run the axis through a small silver stirrup *c r*, and suspend the whole by a fine silk fiber, *r t*, attached to a fixed point *t*; the bar *P S* will be observed gradually to assume a definite and oblique position, *p n*, inclining in these latitudes its north pole *P*, nearly 70° degrees below the horizontal line, turning at the same time into a plane deviating from the plane of the meridian by a given angular quantity; the lower extremity having turned towards the north, and the other extremity towards the south; and it may be likewise observed, on the principle already stated (17), that the extremities which have thus turned the one towards the north and the other towards the south will have been derived from the opposite poles of the lodestone or magnet by which it has been magnetized.

22. This experiment requires considerable mechanical skill and care in the preparation and balance of the bar, so as to poise it accurately about its center of gravity. A very straight piece of cylindrical steel wire, which is generally sufficiently hard to retain polarity, may be employed for the purpose, or the steel of which the bar is made may be also rendered sufficiently hard to retain a magnetic state by simple hammering on the anvil, and yet admit of its being drilled and worked. The process of hardening after the requisite balance has been effected is liable to warp the steel and vitiate the experiment. We may, if we thought it desirable, harden the extremities only by dipping them at a cherry-red heat into cold water; but for this and the following experiments it is desirable to employ naturally hard steel.

23. If the bar be again applied to the lodestone or magnet, but in a direction the reverse of that by which its previous magnetic condition was excited (16, Experiment 5), that is to say, if the north pole of the bar rest on the north pole of the lodestone, and the south pole on the south pole of the lodestone, then, if the experiment be carefully made, we may totally and exactly destroy the magnetism previously excited, or, by continuing the magnetizing process (16), reverse the poles and magnetize the bar in the opposite direction, that is to say, induce a north pole in the extremity which was before a south pole, and a south pole in the extremity which was before a north pole.

EXPERIMENT 8.—Let the bar be rendered neutral by an equal and reverse process of magnetizing (16); replace it on the axis as before, Experiment 7. It will be again indifferent as to position, and will remain perfectly horizontal.

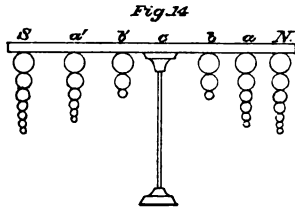
EXPERIMENT 9.—Pass the bar across the poles of the lodestone (16) so as to magnetize it in an opposite direction to that in the former experiment (7); replace the bar on its axis, the phenomena before observed (21) will reappear, but the extremity which before inclined and pointed north will now be raised and will point south, and conversely the extremity which was before raised and pointed south will now be inclined and will point north.

It is not difficult, after a little experience, to destroy exactly the previous magnetism by an equal and reverse process of magnetizing (16); it may be minutely affected by small final contacts with the similar pole of the lodestone, so as to cause the similar polarities to repulse and destroy each other (14); the neutrality may be considered as having been sufficiently effected if on plunging the ends of the bar into soft iron filings the filings do not adhere magnetically to the poles.

24. The dip or inclination, together with the direction of the magnetic needle, is not everywhere alike, especially the dip, which varies from the equatorial parts of our globe, where it is 0, to the polar regions where it is a maximum of 90°. The direction is less variable, it being in some places a little to the east of the north, in others a little

to the west, and in some points of the earth's surface there is no variation.

25. The force developed in a bar of steel rendered magnetic by artificial means is greatest at the two extremities or poles of the bar, from whence it is found to decrease toward the center, or some point intermediate between the two poles in which the force is no longer apparent.



EXPERIMENT 10.—Take a powerful magnetic bar, N S, Fig. 14, about 2 feet in length, an inch wide, and three-tenths of an inch thick. Let this bar be equally hardened throughout its length, and be uniformly

magnetized. Place it on an elevated point of support, *c*, as represented in the figure. Apply now at each extremity, N S, and at any given points, *a b*, and *a' b'*, intermediate between the extremities, N S, and the center, *c*, a series of small rings of soft iron wire, varying from three-fourths of an inch to one-fourth of an inch in diameter, and formed of wire of one-eighth to one-sixteenth of an inch in thickness. The number of rings of equal size which may be thus suspended in series (4) will vary throughout the distance between the center, *c*, and either extremity, N S, of the bar. The number which can be sustained at the poles, N S, being greater than at points, *a a'*, nearer the center, and the number which can be supported at certain points, *a a'*, will be greater than the number which can be supported at other points, *b b'*, within these, nearer the center, *c*, and so on until we arrive at a point, *c*, in which no attractive force is apparent.

The variable attractive force between the center and poles of the magnetic bar may be very beautifully observed by the simple balance, Fig. 28. By passing the bar from point to point under the suspended iron, and regulating the distance to the same point by a divided scale, the increased attraction on each point, as we approach either pole, may be minutely determined. We have only to select such distances as will enable us to observe the increasing force without oversetting the beam of the balance.

26. The points in which the force is absolutely at zero will be found in a line passing across the surface of the bar transversely to its length, and, if the bar have been carefully magnetized (16), will divide it into two equal parts. It will consequently be at the center of the bar. This line has been termed the *mean* or *neutral line* of that surface. In a similar way the points of greatest attraction will be found in two similar lines parallel to the mean line and at each extremity of the bar; these lines have been termed the *lines of the poles*. A line passing longitudinally through the center of the mean and polar lines, and dividing the bar into equal longitudinal parts, has been termed the *axial line* of that surface. The point of intersection of the axial and

mean lines has been termed the *magnetic center*, and of the axial and polar lines, the *magnetic poles* of that surface.

If each surface of the bar be similarly magnetized (20), so that the magnetism of the opposite and homologous points is equally and similarly developed, then all these points and lines on each surface may be taken to coincide and concentrate in the substance of the bar, giving to the bar an ideal transverse and longitudinal magnetic axis, or a magnetic center and two magnetic poles.

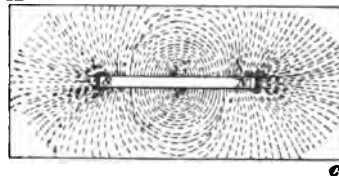
The term *pole*, it is to be observed, has been occasionally employed in other senses; each half of the bar, for example, has been termed a *pole*. It has been also used to designate a sort of ideal point within each extremity of the bar, in which all the forces may be conceived to be collected, and to be the same as if proceeding from every point of each polar half of the bar—much in the same way as we conceive the existence of a point of concentration of force within any material substance, and which we term the center of gravity.

27. In magnetizing a bar of hardened steel by artificial magnets (20), it is requisite to touch each surface in precisely the same way, and stop the process exactly at the center (20); that is, if we require each surface to be alike and the bar to be rendered uniformly magnetic from its center to the extremities: in fact, the superficial boundaries of the bar of steel, of very sensible thickness, may be considered, when magnetized in the common way (21), as so many distinct laminæ, each of which may be taken magnetically as separate systems, so that the center and poles of the one surface may fall differently to those of the other. It is by no means easy to obtain a magnetic bar extremely perfect as an experimental agent. We require, in the first place, steel of a uniform texture and equally hard in every point, and to be magnetized in such way as to render the magnetic condition of each surface identical and coincident.

28. The position of the magnetic center and poles of each surface, together with the general magnetic condition of the bar, and the reciprocal attractions, repulsions, and neutralization of the opposite forces (14), may be very beautifully shown in the following way.

EXPERIMENT 11.—Stretch a piece of common drawing paper on an open frame, A C, Fig. 15, and place it over a hard steel bar, S N, regularly and powerfully magnetic; project on the paper over the bar, through a small muslin or lawn sieve, some fine iron dust or filings; the particles will arrange themselves in a series of curved lines of magnetic force proceeding from the homologous or similar points on each side of the middle of the bar, some uniting about the magnetic center, others standing out at the extremities as if repelled from the poles, N S, and tending to turn at considerable distances into other curved lines of force, to unite their branches between the opposite

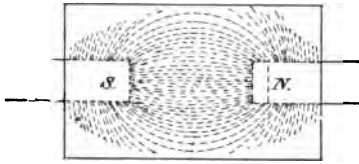
Fig. 15



poles. This experiment may be rendered more decisive by slightly tapping the finger on the paper, so as to give the particles a little vibration.

EXPERIMENT 12.—Oppose the dissimilar poles S N, Fig. 16, of two

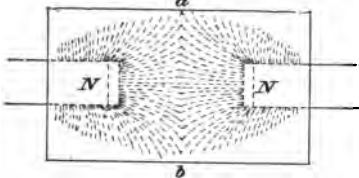
Fig. 16.



of reciprocal attraction.

EXPERIMENT 13.—Change the position of one of the bars so as to

Fig. 17.

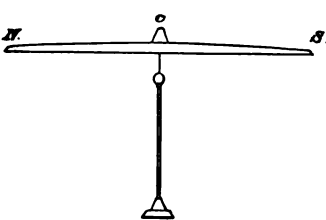


oppose two similar poles, N N, Fig. 17; the lines of force will then appear to be conflicting lines; the repulsive forces will cause a straight line *a, b*, to appear on the open space or field between the poles, from which the iron dust stands out transversely. At this line, the opposed forces on either side are apparently struggling with each other, being exerted in repulsive directions from the opposed poles.

We have in these phenomena satisfactory visual evidence of the existence of two distinct forces—of their reciprocal attractions and repulsions, and their mutual neutralization.

29. A light magnetic bar, N S, Fig. 18, or a small magnetic steel cylinder, of great comparative length, has been

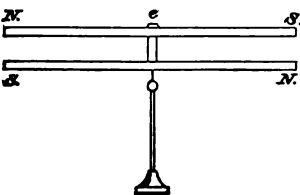
Fig. 18.



termed a *magnetic needle*. When delicately poised on a central point, *c*, so as to retain a horizontal position and move freely in a horizontal plane, it has been termed the *horizontal needle*. When poised on a fine central axis, so as to move freely in a vertical plane, it has been termed a *vertical* or *dipping needle*. If suspended, as in Fig. 13, so as to have motion in both a horizontal and vertical plane, it has been termed the *horizontal and vertical needle*.

Two needles, N S, S N, Fig. 19, precisely equal and similar, poised upon a fine center, *c*, and fixed to each other with their opposite poles, N S,

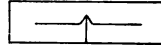
Fig. 19.



S N, one immediately over the other, form what is termed an *astatic needle*. In this combination, the directive force of the needles may be considered as being altogether neutralized, or nearly so; since it is not only exerted in two equal and opposite directions, but the dissimilar polarities, N S, S N, tend to neutralize each other.

30. Instruments for ascertaining whether a substance has polarity or not, and for detecting the presence and kind of force in operation, have been termed *magnetoscopes*. The horizontal, vertical, and astatic needles (29) may be considered as instruments of this kind. The most simple kind of magnetoscope is a small horizontal needle, about an inch in length, delicately suspended by a fine silk fiber, or otherwise set upon a fine point and agate center, within a small wood or glass case, as represented in the annexed Fig. 20, and so set as to admit of some degree of dip or depression of either pole, as well as a perfect motion in a horizontal plane.

Fig. 20

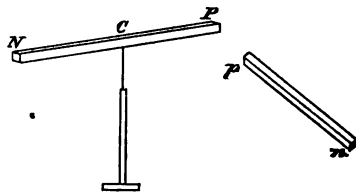


From the attractive and repulsive forces of similar and dissimilar poles (14), it is evident, from the kind of effect produced on the poles of the magnetoscope, we may always determine the presence or kind of polarity acting on it. Thus, if such an instrument as that just described, Fig. 20, be glided along the surface of any given substance without any attractive or repulsive effect being apparent, such a substance may be considered as non-magnetic. If, on the contrary, we find both poles of the instrument everywhere attracted indifferently, then we may infer that the substance is a magnetic substance: such would be the case with a piece of common soft iron. Should we find certain points attractive of one of the poles of the small needle, and repulsive of the other, then we may infer that not only is the substance a magnetic substance, but that it has also polarity, or is a magnet.

RECIPROCAL ACTION OF MAGNETIC BARS.

31. If a magnetic bar be poised horizontally on a central point (29), and a piece of soft iron be presented to it, the iron will be found attractive of either pole. Such, however, is not the case on presenting to it a piece of magnetic steel. In this case, as in that of the native magnet Fig. 5, it is found that the similar poles, or those which, when the masses are suspended, point in the same direction, repel each other; whilst the opposite or dissimilar poles attract.

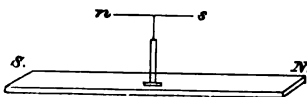
Fig. 21.



EXPERIMENT 14.—Suspend a magnetic bar, N P, Fig. 21, on a fine center, *c*, and present to one of its poles, P, the similar pole *p* of a second bar, *p n*, the pole P will immediately recede, and be apparently repulsed; present the pole *p* to the opposite pole, N, the reverse of this will ensue—the bar N P will be apparently attracted.

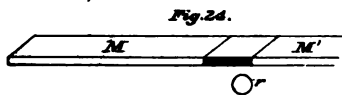
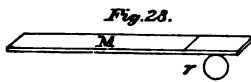
EXPERIMENT 15.—Place a magnetic needle or bar, *n s*, Fig. 22, immediately over a strongly magnetized bar S N; the needle, as in Experiment 4 (11), with the native magnet, will rest in no other direction but that in which the opposite poles S *n* and *s* N, are opposed to each other.

Fig. 22.



32. These reciprocal attractions and repulsions may be taken as further evidence of the operation of two opposite forces, or magnetic elements, repulsive of themselves, but attractive of each other (14), and which, when intimately combined, exactly neutralize or compensate their respective attractions and repulsions, constituting, in their combined state, what may be termed the *latent* magnetism of the bar. When separate, and removed in a greater or less degree from their reciprocal influence, they become more or less active, and are thus in a condition to operate on the latent magnetism of other ferruginous matter (4). The neutralization of these forces, and their tendency to unite, is well illustrated in the following way :

EXPERIMENT 16.—Place a short piece of soft iron, T, Fig. 23, about 5 inches long, in contact with a powerful magnetic bar, M', which may be about 2 feet in length. Suspend from the iron, T, by the attractive force communicated to it, a steel or iron ring, *r*. Under these circumstances, let a second similar bar, M', Fig. 24, be applied to the opposite extremity of the iron T, and in such a way that the dissimilar poles *ns* of the two bars may operate on each other through the substance of the iron; the result will be that the two magnetic elements will so exactly neutralize each other as to cause the ring *r* to fall away, the attractive force before imparted to the iron by the pole of the magnet M being in this case completely destroyed.



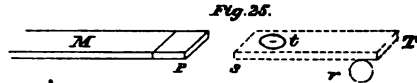
MAGNETIC INFLUENCE OR INDUCTION.

33. We have just seen (32), Experiment 16, that when a piece of soft iron is brought into contact with a magnetic pole it immediately acquires an attractive power, as if the magnetism of the pole had spread out and pervaded the iron. In fact, if we examine a piece of iron thus circumstanced by means of the magnetoscope (30), we find the same polarity continued throughout the iron; it will everywhere attract one pole of the magnetoscope and repulse the opposite pole. If, however, we separate the iron T, Fig. 23, from the magnet, and retain it at a short distance from the magnetic pole, then a new case appears to arise: that portion of the iron next the magnet will have an opposite polarity to that of the pole to which it is opposed; the two magnetic elements (14) resident in the iron will, in fact, become separated; one of them will be sensible at the extremity next the magnet, and the other at its distant extremity—a result which we might expect to follow from the repulsion of the similar elements and the attraction of the opposite elements (14). This separation of the latent magnetism of the iron into its constituent elements has been termed *magnetic induction*. It is altogether a temporary state or condition of the iron sustained by the influence of a magnetic pole, and vanishes as soon as that influence is withdrawn.

EXPERIMENT 17.—Place the small magnetoscope (30), Fig. 20, on the

mass of soft iron T, Fig. 23, Experiment 16, in contact with one of the poles of the magnet M, suppose the north pole; it will be found that the similar pole of the magnetoscope will be everywhere repulsed and thrown up; and if we pass the instrument along the side of the iron, the opposite pole, that is to say, the south pole, will be everywhere attracted. Hence (30) a north polarity pervades the iron T, and the south polarity or dissimilar element has been neutralized by the opposite element or power of the magnetic pole.

EXPERIMENT 18.—Let the iron T be now separated from the magnet M by a given distance, P S, as shown in the annexed Fig. 25; then, on applying the magnet-



oscope *t* to the surface as before, it will be found that one of its poles will be repulsed by the extremity S, and attracted by the distant extremity T; and if we apply a ring of soft iron, *r*, to the extremity T, it will be held up solely by the influence of the magnet operating through the iron *r*, at a distance. Let, for example, the opposed pole P be a north pole, then the near end, S, of the iron will be a south pole, and will repulse the south pole of the magnetoscope, which will be thrown up. On applying the instrument to the distant extremity, T, the reverse of this will occur; that extremity will be found to be a north pole, and will repulse the north pole of the magnetoscope, so that the north pole P of the magnet will vanish as it were on the iron, and re-appear at its distant extremity; and the iron will, under the influence of the magnetic pole, P, become itself a temporary magnet, having its two poles and mean line, as in any other magnet of a permanent kind. A similar result will be arrived at in passing the magnetoscope along the side of the iron, as in the last experiment.

34. It is, however, to be observed, that the position of the mean line will vary with the distance of the iron from the magnetic pole, and will approach the center of the iron as we increase its distance from the pole, and conversely will approach the near extremity as we decrease its distance from the same pole; so that on making contact with the magnet the mean line vanishes, and the whole mass exhibits the same polarity as the pole of the magnet, resolving itself into the case already illustrated.

35. We may perceive by these experiments that the influence of the pole P has been such as to separate the two magnetic elements resident in the iron, attracting and rendering sensible, in points toward the near extremity S, the element opposite to that of the pole P, and repulsing and rendering sensible the similar element in points more remote and extending to the distant extremity T. The iron has thus become, under the influence of P, a temporary magnet. If, therefore, we neutralize the polarity of P, by presenting to it the opposite pole of an equal and similar bar, this induced magnetic state of the iron T will immediately vanish.

EXPERIMENT 19.—Suspend, as shown in the last experiment, Fig.

25, one or more rings of steel or soft iron, at the extremity of the iron, T, and then bring the opposite pole S of an equal and similar bar M', Fig. 26, gradually over the pole P of the inducing magnet M; the ring *r* will be then observed to fall away from the iron T, by the neutralization of the opposite forces resident in the poles P S of the two magnets M M'; and these actions will all take place at a distance, without any near contact of the respective masses.

It is desirable in these experiments that the iron should be very soft, and be in no sensible degree magnetic; it should be of the same breadth and depth as the magnet, and may be about one-fourth of the length. Bars about 2 feet long, $1\frac{1}{2}$ inches wide, and three-eighths of an inch thick are well adapted to these investigations; they may, however, be successfully pursued with much smaller bars.

36. The two magnetic forces being thus separable by induction, and made to appear, as it were, in different parts of a mass of iron, it might be inferred that if we could remove the distant extremity of the iron T, Fig. 25, whilst under the influence of the magnet M, we should thereby obtain one of the elements in an insulated state, much in the same way as we obtain the positive or negative force in electricity, under similar circumstances. Such, however, is not the case; on the removal of a distant portion of the iron, all traces of polarity vanish.

EXPERIMENT 20.—Let the iron T, Fig. 27, be constructed in two parts *m n*, closely ground together, the part *n* being about 2 inches long, and *m* 3 inches long. Place this compound mass under the influence of the magnet M, so that the extremity *n* may become attractive of a ring of soft steel, and repulse or attract one pole of the magnetoscope; fix the iron T and magnet M, and then withdraw the distant portion *n*. The extremity *n* will no longer repulse one of the poles of the magnetoscope, but will operate equally on both, showing that its polarity has vanished; neither will it exhibit any attractive power on soft iron or steel; the induced force has hence disappeared.

We may conclude from this experiment, that either both the elements were always present, and had now recombined, or otherwise that the opposite element had been derived from surrounding matter—a supposition scarcely tenable in the present state of our knowledge of magnetic phenomena. Whatever be the nature of the agency upon which these curious facts depend, there is every ground for supposing that the two elementary forces (14) never leave the particles of matter with which they are associated. Thus, in the communication of magnetism by the lodestone to hardened steel (16), and from one piece of steel to another without limit (16), neither the lodestone nor the artificial magnet loses any of its inherent power; nothing, therefore, appears to be communi-

Fig. 26.

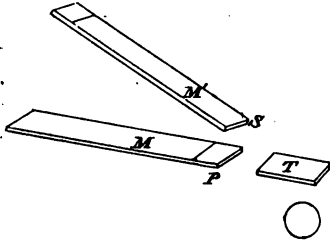


Fig. 27.



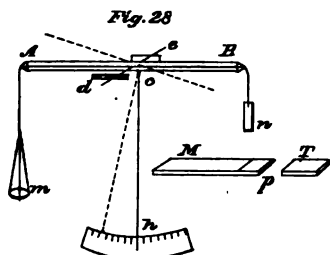
cated; the whole result is entirely a species of molecular excitation, or a calling into sensible activity certain forces already existing in the magnetic substance (33), and which, under ordinary circumstances, remain in a quiescent or neutral state. No means yet devised have ever insulated these forces in such way as to enable us to obtain one of them only, independently of the other. We cannot, for example, produce a magnetic bar having a single pole; for although we touch one extremity of the bar only with one pole of the lodestone (16), still two poles will appear in the bar, although the one induced by the presence of the other may not be so forcible.

EXPERIMENT 21.—Magnetize regularly a bar of very highly tempered steel, break it into two parts exactly in its mean line (26) or magnetic center, on one side of which we have one kind of polarity, and on the opposite side the reverse polarity (26). Examine the fractured ends of each piece by the magnetoscope; two poles will be found to exist in the line of fracture, that is to say, in the points which before appeared neutral. If we again break the two parts each into two other parts, the same result ensues, and so on without limit. The only exception will be that the magnetic center and mean line (26) may not fall at the center of the fractured parts. Such experiments are easily made with bars very highly tempered (87). It appears, therefore, that in every instance of magnetic excitation the two forces are present, and are both developed together.

REACTIVE FORCE OF IRON AND MAGNETS ON EACH OTHER.

37. The influence of a magnetic pole in inducing in a mass of iron a temporary magnetic state being such as to cause an opposite or dissimilar polarity to appear at the proximate parts of the iron, and the same kind of polarity in the more remote or distant parts, we should expect to find a given amount of neutralization of the magnetic pole or reactive force apparent, much in the same way as if a second permanent and opposite magnetic pole were opposed to the pole of the inducing magnet, and such is observed to be the case.

EXPERIMENT 22.—Run a fine needle, *d e*, Fig. 28, transversely and perpendicularly through the center of a light beam of clean grained deal, *A B*, about 14 inches in length and one-fourth of an inch square, so as to give the beam a delicate axis of support. Mount this beam on



two small cheeks of glass, *d e*, supported in any convenient way. Suspend a small cylinder of iron, *n*, from one of the arms, *B*, by a light silk thread, and counterpoise it by weights placed in a small scalepan, *m*, suspended in a similar way from the opposite arm, *A*; the iron cylinder may be about $1\frac{1}{2}$ inches long and one-fifth of an inch in diameter; it should be carefully constructed of very soft iron. Attached to the center of the beam under the axis is a light index of reed, *c h*, movable over a graduated arc, *h*.

The beam being accurately poised, and the index, $c h$, at zero of the arc, place one of the poles of a powerfully magnetic bar, M , at such a distance beneath the suspended iron n as will incline the beam $A B$ without oversetting the balance, and bring the index into the position of the dotted line, that is, to a certain division of the arc. The beam being thus inclined, oppose to the pole p a mass of soft iron, T , of equal breadth and thickness to the magnet M . The beam will immediately tend to right itself, and the index will again decline, showing the neutralizing or reactive influence of the iron on the pole of the magnet M .

38. It will be convenient, in experiments of this kind, to place the iron and magnet on a graduated scale resting on a small table, the elevation of which may be varied, so as to measure the distance between the extremities of the magnet and iron, and at the same time, by means of a vertical graduated scale, note the distance between the magnet and suspended iron n .

EXPERIMENT 23.—This reactive force of the iron T on the magnet M will be also apparent in placing the iron immediately under the magnetic pole, as at p , Fig. 28, but it will not be so sensibly indicated as in the last case; it will be also evident in placing the iron over the magnetic pole, immediately between the magnet and suspended iron, in which case, by operating more directly on the nearest points, it is powerfully apparent. The iron has been said, in this case, to screen off or intercept the magnetism of the bar M —a result commonly attributed to a sort of insulating power or magnetic opacity in the iron, but which evidently arises solely from the annihilation of the attractive force to a greater or less extent (35); the same result being obtained when the iron is placed either beneath or at the extremity of the bar. We have merely to observe in this last case that the iron must not be so near the suspended cylinder, nor the magnet so near the iron, as would affect the balance by induction upon the intervening mass (33).

39. The distance within the magnet at which the neutralizing effect of the iron is sensible when placed next its extremity has no limit, but is felt in every point up to the central parts of the bar in which the least degree of force can be detected.

EXPERIMENT 24.—This may be easily observed by bringing given points of the bar under the suspended cylinders, and opposing a mass of iron to the magnetic pole at a given distance. The amount of neutralization depends, as may be conceived, on the force induced in the iron, and on its distance from the magnet. Large masses of iron up to a certain limit, and varying with the degree of force in the magnetic bar, have a greater neutralizing influence than smaller masses, and it appears to be of no moment to the experiment whether the iron be opposed to the magnet in the direction of its length, or be placed transversely to the pole.

EXPERIMENT 25.—Repeat the preceding experiment with bars of different degrees of power and masses of iron varying in dimensions; the respective neutralizing effects will be easily determined.

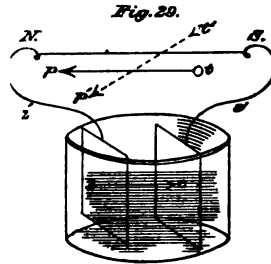
CHAPTER III.

THE ELECTRO-MAGNET.

Reciprocal action of common magnetism and a voltaic current—Electro-magnetic forces—Magnetic deflections and rotations—Electro-magnetic multiplier—Steel magnetized by electrical currents—Electro-magnets and the laws of the development of magnetism by voltaic electricity.

40. The next series of phenomena claiming attention arises out of a property peculiar to natural and artificial magnets, by which they tend, when freely suspended, to arrange themselves in a certain relative position to a wire carrying a current of voltaic electricity. These phenomena have been hence termed electro-magnetic, and although of sufficient moment and extent to come under a separate and peculiar branch of physical science, yet so far demand a brief notice here, as constituting a very important property of the natural and artificial magnet.

With a view to a clear conception of these reciprocal magnetic and voltaic actions, it is requisite to understand that two plates of zinc and copper, z c , Fig. 29, placed near each other in a vessel of dilute acid, and connected by a metallic circuit, c' S N z' , turned or directed in any manner, give rise during the solution of the zinc in the acid to a peculiar electro-chemical action, by which a current of electricity is supposed to flow from the zinc plate z in the direction of the small arrow, through the acid upon the copper plate c , and from thence through the metallic circuit c' S N z' , back again upon the zinc plate z . A combination of this kind has been termed a voltaic circuit, and the metallic circuit, c' S N z' the uniting wire.



EXPERIMENT 26.—This understood, let S N be a perfectly straight portion of this circuit, which as a standard of reference as to position we will suppose to be in the direction of the magnetic meridian (7). Let p t be a magnetic needle suspended below and parallel to N S ; then, directly we complete the communications N z' z — S c' c with the zinc and copper plates z c , the needle p t varies from the meridian, and tends to place itself across the wire N S , and in such way that whichever pole of the needle is next the copper plate c , that pole moves to the right hand or towards the east. If, therefore, as in Fig. 29, the current flow over the needle from c to z through the wire S N from south to north, and the observer be looking over the wire in the same direction—then the south pole t next the copper plate c turns to his right hand or to the

east, and the north pole p to his left hand or west. If we suppose the position of the plates c and z to be exchanged, and the direction of the current reversed, by connecting the extremity N with c and the extremity S with z , so as to cause the current to flow from north to south, then these deflections are all reversed. The south pole t now goes to the westward, and the north pole p to the eastward.

EXPERIMENT 27.—Place the needle above and parallel to the wire SN then the reverse of all the former deflections will be obtained. When the current, therefore, flows from south to north, the south pole t , which before went to the east when the needle was below the current, now goes to the west when the needle is above the current; if we reverse the current, and cause it to flow from north to south, then these deflections are again reversed.

41. The following Table I comprises, under a perspicuous form, these several deflections, together with the relative positions of the needle and direction of the current:

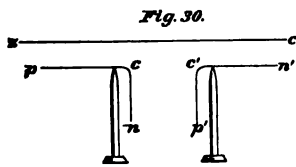
TABLE I.

Wire over the Needle.		Wire under the Needle.	
Direction of current.	Deflections.	Direction of current.	Deflections.
(a) South to north. {	North pole to the left.	(c) South to north. {	North pole to the right.
	South pole to the right.		South pole to the left.
(b) North to south. {	North pole to the right.	(d) North to south. {	North pole to the left.
	South pole to the left.		South pole to the right.

42. That these deflections arise from a distinct and independent action of the current on each pole of the needle at the same instant is evident from the following experiment:

EXPERIMENT 28.—Let $p\ c\ n$ and $n'\ c'\ p'$, Fig. 30, be two light magnetic bars, bent so as to place one half the bar $p\ c$ at right angles to the other half, $n\ c$; balance these magnets on fine centers, $c\ c'$, immediately under a wire, cz , to be connected with the zinc and copper plates of the voltaic circuit; take cz in the direction of the magnetic meridian as before, and suppose the poles $p\ n'$ of the magnets in the same straight line, $p\ c\ c'\ n'$. We may, in this arrangement, take the distant vertical poles $n\ p'$ of these bars to be without the limit of the influence of any current passing through cz ; connect the wire $z\ c$ at points $z\ c$ with the zinc and copper plates of the voltaic circuit, Fig. 29; both the magnets will be moved, and in opposite directions, as specified in the above table.

It may be seen, by reference to this table, that the same deflections are produced by a current flowing over the needle from south to north (a) as by a current flowing under the needle from north to south (d);

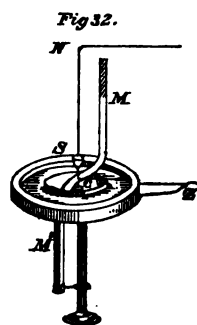


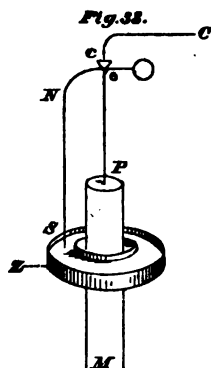
and, reciprocally, a current flowing under the needle from south to north (*c*) produces the same deflections as in flowing over the needle from north to south (*b*). Hence, if, in the last experiment, Fig. 30, one of the bars, *p' c' n'*, be raised above and parallel to the wire *c z*, whilst the other, *p c n*, remains beneath it, then, on transmitting a current through the wire, both the bars move to the same side, that is, are deflected in the same direction. It is not requisite, in these experiments, to place the bars or needle immediately over or under the wire *S N*; it is sufficient that the needle be near and parallel to the wire, either above or below it.

43. If the needle be immediately in the plane of the uniting wire on either side of it, no motion is obtained in that plane; but if it be suspended in a vertical plane, on a horizontal axis, so as to admit of a deflection of inclination, then it tends to place itself across the wire as before. If the needle be on the east side of the uniting wire, that is, on the right hand, taking the current and direction as at first, then the south pole next the copper side of the battery rises above the horizontal plane, and the north pole next the zinc plate dips. If the current be reversed, the deflections are also reversed. If the needle be placed on the left hand or west side of the uniting wire, then the south pole next the copper plate dips, and the opposite north pole rises; by reversing the direction of the current these deflections are again reversed.

44. It is apparent, from the successive directions of the bar as it becomes placed above, at the sides, or below the wire *S N*, that the force affecting the magnet is a force transverse to the pole of the bar, by which, if the bar had complete freedom of motion in every direction, the poles would actually turn round the wire, but in different directions; and, conversely, supposing the bar fixed and the wire *S N* carrying the current free to move, then those parts of the wire parallel to the magnet would rotate about the magnetic poles in opposite directions in a similar way. If both are supposed free to move in any direction, then the wire and magnet would turn round each other; and such is really found to happen, giving rise to a very beautiful and most important series of electro-magnetic actions.

EXPERIMENT 29.—Let a magnetic bar, *M M'*, Fig. 32, be bent so as to produce a short oblique portion at the middle of the bar, with two vertical arms, *M M'*; poise it on a fine central point, *c*, and let a wire, *N S*, be placed near and parallel to one of the arms, *M*. Then, supposing a descending current to flow from the copper plate, *c*, Fig. 29 (40), through the wire in the direction *N S* upon the zinc plate *Z*, the magnet *M* revolves about the wire *N S*, upon the central point *c*; and if the north pole of the bar be uppermost, the motion will be direct, or from the left hand to the right.



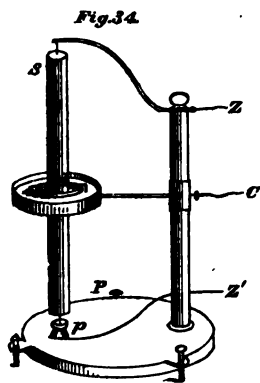


EXPERIMENT 30.—Conversely, if the magnet *M* be fixed as in the annexed Fig. 33, and the wire *N S* be movable on a fine center, *O*, then, on transmitting the current as before through the wire *N S*, it immediately revolves about the pole *P* of the magnet, with a direct screw-motion, supposing the current to descend the wire, and the pole *P* to be a north pole. To enable these motions to go on without disturbing the progress of the current and the connections with the voltaic plates, the movable parts dip into small cups and cisterns containing mercury, and with which the plates of the voltaic

circuit, Fig. 29, communicate, as indicated in the figures.

45. The tangential or transverse force, by which a magnetic pole is caused to revolve about a wire transmitting a current of voltaic electricity, is equally apparent when the magnetic bar itself becomes the conjunctive wire of the battery; so that an electrical current flowing over or through a magnetic bar from one of its poles to the equator or from the equator to either of the poles, causes such a bar to revolve upon its axis, the requisite mechanical arrangements for motion being complete.

EXPERIMENT 31.—Let a magnetic bar, *S P*, Fig. 34, be mounted vertically between two delicate centers; the bar may be about 18 inches in length, 1 inch wide, and one-fourth of an inch thick. Let an electrical current (40) be caused to flow from either of the poles *P S* to the equator *d*, or from *d* to either of the poles *P*; the bar will immediately revolve upon its axis, *P S*, the direction of the motion being such that, supposing the bar to rest upon its north pole, *P*, the center *d* being in communication with the copper plate of the battery, *C*, and either or both of the poles *P S* in communication with the zinc plate *Z*, electrical currents will flow



from the equator *d* to the poles (40), and the bar will revolve from left to right, as in the motion of the hands of a watch. By reversing the communication with the voltaic plates, that is, placing the poles *P S* in connection with the copper plate, and the center *d* with the zinc plate, the electrical current will flow from the poles to the equator *d*. In this case, the direction of the motion will be the reverse of the former.

EXPERIMENT 32.—If the position of the magnet be changed, that is, if we place it to rest with its south pole below, then, the communication with the voltaic circle remaining as in the first instance, we also reverse the motion. If now the communications be changed as in the last instance, we again reverse the motion, and obtain, as at first, a motion from left to right.

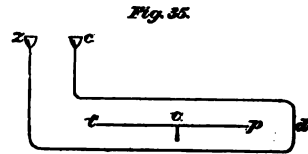
To facilitate the passing of the electrical current over the magnet, the

bar is supported between fine centers, P S, by a light vertical column fixed on a firm base; a small ring or cistern of mercury, d , also supported from the vertical column, surrounds the equator of the bar; the bar turns within this, and it is connected with the mercury in turning by a small bent wire dipping into the cistern; the lower center P turns upon an agate contained in a small cup, p , connected with the point Z' ; this cup contains a small globule of mercury, to keep up the metallic connection with the magnet; there is a similar globule in a small cavity at the upper end of the bar for the center S; this upper center is supported by a wire extending from the head of the pillar Z Z'. It is here evident that, in connecting the points C Z or C Z' with the plates of the voltaic circuit (40), an electrical current will flow between these points through C d S Z, or C d p Z', the direction depending on the respective connections with the zinc or copper plate of the circuit (40).

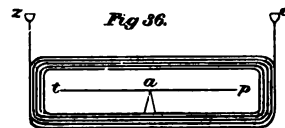
A recollection of the relative direction of the motions we have been describing will be facilitated by keeping in mind the following simple formula: A descending current moves a north pole to the right hand, or will give rise to a direct screw-motion; from this simple fact all other relative motions are easily determined.

46. The reciprocal action of a magnetic needle and uniting wire (40), together with the series of deflections in given directions shown in Table I (41), have led to the invention of a very important magnetical instrument, termed the electro-magnetic multiplier, or galvanometer, by which extremely small magnetic and electro-magnetic forces may be detected and measured.

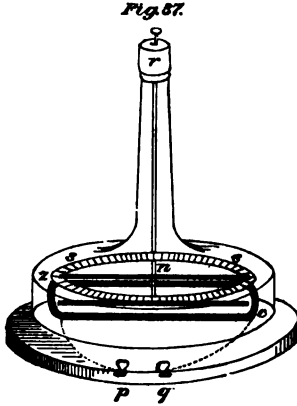
It will be apparent, by inspection of Table I, as already observed (42), that a current flowing both above and below a needle, in opposite directions, deflects the needle in the same direction; hence it follows that if a magnetic needle, $p t$, Fig. 35, be suspended on a delicate center, c , within the bight of a returning wire, $z d c$, and the extremities, $z c$, of the wire connected with the zinc and copper plates of the voltaic circle by means of two little cups containing mercury, then a current will flow longitudinally round the needle, both above and below it, and in opposite directions; that is to say, in the direction $c d$ above the needle, and in the direction $d z$ under it; the effect of this will be to deflect the needle with twice the power by which it would be deflected with a single current only, as in Fig. 29 (40).



If we imagine the wire $z d c$ to be several times turned longitudinally about the needle, as in the annexed Fig. 36, then the effect would be still further increased; it would, in fact, become multiplied in proportion to the number of turns of the wire, which would represent so many additional currents. It is only requisite to cover the wire with silk thread or some other im-



perfect or non-conducting matter, so as to avoid metallic communication between the coils, and oblige the current to traverse the whole length of the wire. This is the principle upon which the electro-magnetic multiplier rests, and the delicacy of the effect is such that the needle will become deflected by the immersion of two pieces of zinc and platinum



wire less than one-eighth of an inch long and one-fiftieth of an inch in diameter, in water slightly acidulated. The annexed Fig. 37 represents this instrument under one of its forms. Two magnetic needles with their poles reversed to each other are fixed on a central rigid axis, so as to neutralize the directive power of the needles and render the system astatic (29), or nearly so, merely allowing a sufficient force to bring the whole into the meridian. This system is suspended by two parallel threads of unspun silk, $r n$, one of the needles being within a rectangular coil of wire, $z d c$, and the other needle immediately

without it, and over the upper part of the coil. The wire $z c$ is covered with silk thread, so that the coils may not have metallic communication, and the extremities $p q$ are brought out near each other, and terminate in small cups, $p q$, containing a little mercury, for the better convenience of communicating a current to the coil from any given source. The coils are separated a little near the center, to allow the axis of the astatic system of the two needles to pass through them.

The slightest current transmitted through the coil from p to q , or q to p , causes the needles to deviate from their constant position; both the needles, as is evident, will be impelled in the same direction; the lower needle being in the position just described, Figs. 35 and 36, whilst the upper needle, its poles being reversed, is impelled in the same direction by the upper side of the coil.

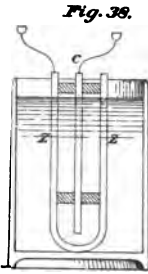
The threads of the double or bifilar suspension, $r n$, in tending to cross each other as the needles turn, give rise to a reactive force which may be set against the deflective force employed to measure it; for this purpose a graduated circle, $s s$, is fixed under or round the upper needle, so that the angle of deflection may be accurately estimated. If the earth's directive force be completely neutralized by the reversed positions of the needles, then this would be the only force opposed to the deflective force; if not, then it becomes mixed with the little directive power left in the system, but which is generally so small as not to be of much moment.

The instrument is set upon a convenient stand, and may be inclosed within a glass shade; the bifilar suspension being sustained within a tube of glass.

Various forms of the electro-magnetic multiplier have been devised;

several have a single needle only, as in the arrangement Fig. 36, which for all ordinary purposes answers extremely well, and is in some particular instances to be preferred.

47. The simple voltaic circle described in Fig. 29 has been hitherto the only kind of combination referred to, on account of its simplicity; it may, however, be proper to observe that we possess better and more certain forms of this valuable instrument of research. The voltaic circle, invented by Mr. Smee, and termed Smee's battery, is well adapted, and certainly the most convenient, for ordinary purposes. In this arrangement a silver plate, *c*, Fig. 38, coated with platinum, and termed platinized silver, is substituted for the copper plate in the original circle (40); this is inclosed between a double zinc plate, or between two zinc plates, *Z Z*, held firmly against a center block of wood at the upper edges of the plates by a clamp and binding-screw, so that they have metallic communication, and act together as a single plate. The platinized silver plate is prevented from touching the zinc in any part by intermediate non-conducting matter. The current in this arrangement flows as before; that is to say, the platinized silver plate has the same relation to the zinc plate in this circle as the copper plate in the original circle, Fig. 29 (40); the difference is merely in the substance, arrangement, and position.

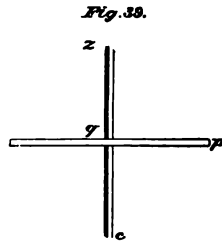


STEEL MAGNETIZED BY THE ELECTRICAL CURRENT.

48. One of the many important results of these discoveries is the means of imparting a high degree of magnetism to iron and steel, and to so great an extent as to give a soft iron rod a lifting power of more than a ton.

We have seen that the electrical and magnetic forces are so related that the one is exerted at right angles to the other; thus a magnetic needle tends to stand directly across the conjunction wire. We derive from this elementary principle a means of disturbing the latent magnetic forces resident in magnetic substances, by which these forces become separated, and the body rendered magnetic, precisely in the same way as effected by the contact of an ordinary magnet (20.)

EXPERIMENT 33.—Place a perfectly neutral bar of hard steel, *p t*, Fig. 39, across a metallic wire, *c z*, uniting the plates of a simple voltaic circle, and as a standard of reference as to direction and position, let the uniting wire, *c z*, be in the line of the magnetic meridian, *c* being its south, and *z* its north extremity. Under these conditions draw the bar *p t* forward and back several times across the wire *c z*, from end to end, finally stopping in the center, *q*; on removal, the bar will be found to have acquired a strong polarity. If the current be



passing from c to z , that is, from south to north, the wire being in this case under the bar, then the east or right-hand extremity, p , will have become a north pole, and the left-hand or west extremity, t , a south pole; which is precisely what would happen from the experimental facts already given (41), and from which it must also follow that by reversing the direction of the current on placing the bar under the needles the resulting polarities would be also reversed.

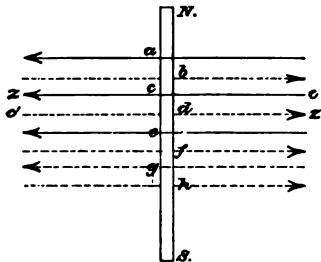
EXPERIMENT 34.—Place the bar $t p$ under the wire $c z$, all other things being the same, and repeat the process of magnetizing as in the last experiment; on removal, the west or left-hand extremity will have become a north pole, and the east or right-hand extremity a south pole. By reversing the current in either of these cases (Experiments 33 and 34) so as to cause it to flow in the direction of $z c$, or from north to south, we again reverse the polarities of each, and may hence obtain the same polarities, whether the bar $p t$ be placed over or under the wire $c z$; that is to say, a current flowing from c to z under the bar will give rise to the same polarities as in flowing from z to c over the bar.

49. As it is important to remember these relative directions and polarities, it may be as well to reduce them to a simple tabular form.

TABLE II.—Showing the relative polarities induced in a bar of steel by the influence of an electrical current, the bar being at right angles to the wire (Fig. 39).

Direction of the current.	Relative position of the north and south poles.	
CURRENT AND CONNECTING WIRE OVER THE BAR.		
Bar under wire:		
(a) South to north.....	{ Positive pole determined to the left..... Negative pole determined to the right..... Positive pole determined to the right..... Negative pole determined to the left..... } Case 1.	
(b) North to south.....		
CURRENT AND CONNECTING WIRE UNDER THE BAR.		
Bar over wire;		
(c) South to north.....	{ Positive pole determined to the right..... Negative pole determined to the left..... Positive pole determined to the left..... Negative pole determined to the right..... } Case 2.	
(d) North to south.....		

50. If we suppose a steel bar, N S, Fig. 40, crossed by several wires, $a b c d$, some above and some beneath the bar, and currents passing through the wires

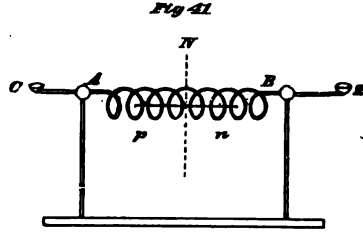


over the bar, all in the same direction, $c z$, and through those under the bar, all in the reverse direction, $c' z'$, such currents would all conspire to determine the north polar element in one direction, and the south polar element in the opposite direction, and the bar would be at once rendered magnetic. If the wires were sufficiently numerous to cross the bar on each point, $a b c d$, &c., from end to end,

numerous to cross the bar on each point, $a b c d$, &c., from end to end,

every point would be acted on, and the resulting magnetic state become thereby powerfully developed.

EXPERIMENT 35.—Let a long piece of copper wire be wound round a piece of glass tube of about one-half an inch or less in diameter, and from 6 to 10 inches in length, so as to produce a helix or spiral, A B, Fig. 41, and mount this spiral between two vertical supports as represented in the figure. Place a perfectly neutral piece of hard steel wire, $p\ n$, of about one-tenth of an inch in



diameter, or a large sewing-needle, within the helix, and connect the extremities A B with the zinc and copper plates of the voltaic circle, the steel, $p\ n$, will become immediately magnetic; in fact, each turn of the spiral causes electrical currents to flow in reverse directions above and below the steel, as just described, Fig. 40. If the coils of the spiral be numerous and close, they may be regarded as parallel circles standing at right angles to the direction of the inclosed wire, and with which the axis of the helix may be made to coincide. The effect of a helix of this kind on a fine magnetic needle placed within it is so powerful that with a strong voltaic current the needle is sometimes caught up and retained on the axis of the spiral, as if liberated from the trammels of gravity.

51. The kind of polarity given to steel or iron thus circumstanced will depend on the direction of the current with reference to the axis of the helix, and this again will depend on the connections with the plates of the voltaic circle and the direction in which the helix is turned. Now, the spiral may evidently be turned either direct, as in the threads of a common corkscrew, forming what is termed a right-handed helix, as in the annexed Fig. 42, or it may be turned in the reverse direction, in which case we have a left-handed helix, as in the annexed Fig. 43.

Fig. 42.



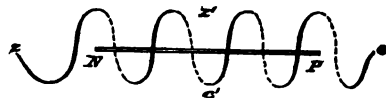
Fig. 43.



EXPERIMENT 36.—If we suppose the helix to be a reverse or left-handed helix, as in the annexed Fig.

44, the current flowing from c to z , round a small cylindrical steel needle or wire, $P\ N$, and the coil standing in the direction of the magnetic meridian

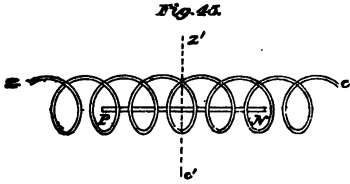
Fig. 44.



$c' z'$, so that the current may flow under the wire in the direction, $c' z'$, from south to north, as indicated by the dotted lines, and over the needle in direction $c' z'$, from north to south, as indicated by the full lines, then any one of the coils $c' z'$ under the wire would fulfill the conditions of Experiment 33, and with the wire itself be faithfully represented in Fig. 39. In this case, as may be seen by Table II, case 12

(c), and case 1 (b), the positive pole P will be determined to the right hand, and the extremity, P, of the wire next the copper plate, c, will be a north pole; by similar reasons the opposite extremity, N, will be a south pole, and next the zinc plate of the battery.

EXPERIMENT 37.—If we take a direct or right-handed helix and an inclosed wire, P N, as in the annexed Fig. 45, and transmit the current as before from c to z, then the reverse of all this occurs; the currents flow *under* the wire from north to south in direction z' he wire from south to north



in direction $c' z'$. Under these conditions, by Table II, case 2 (d), and case 1 (a), the positive pole, P, is determined to the left hand, so that the extremity, P, of the steel cylinder, P N, next the zinc plate becomes a north pole, and, by similar reasoning, the opposite extremity next the copper plate, c, a south pole. Supposing the current to be reversed and to pass through a direct helix from left to right, as from c to z, Fig. 41, the copper plate of the battery being to the left hand, and which is the ordinary form of the experiment, the north pole will be always determined next the zinc plate; that is, to the right hand.

52. It will be useful to the student to remember as a general fact that, supposing (Fig. 41) the observer to be facing the north, N, and the helix, A, B, placed transversely before him, so that its axis may lie east and west, then if the current be *descending* the coils of the spiral directly before him, the north pole is determined to the right hand, and the south pole to the left. Reciprocally, if the current be *ascending* the coils of the spiral directly before him, then the south pole is determined to his right hand, and the north pole to the left. Hence, with a direct helix, the north pole will be always found next the zinc plate, and with a left helix next the copper plate, as may be easily seen by inspecting Figs. 42 and 43, the direction of the currents being either from left to right or right to left.

53. The magnetic power developed in soft iron closely surrounded by heliacal coils transmitting electrical currents all in the same direction is so great that a curved iron rod, during the action of the battery, may be caused to sustain an enormous weight. The usual form of the experiment is as follows:

EXPERIMENT 38.—A cylindrical bolt of soft iron, P T N, Fig. 46, about an inch or more in diameter, and from 30 to 40 inches long, is bent into the horseshoe form as indicated in the figure. It is then surrounded by several long coils of copper wire, z T c, covered with silk or other insulating thread, so as to interrupt all metallic communication or coil with the other; one set of coils is superposed on another, and all the ends of the wires, P N, on each side united into common terminations, z c, to be connected with the voltaic battery.

If when the currents are passing through the coils we apply a soft iron

keeper (10), P N, and cross the projecting poles, it will be held fast with an enormous force, so that several hundred-weight, W, may be suspended without breaking the contact. Electro-magnets of this kind have been made sufficiently powerful to support many tons.

The laws which govern the forces of electro-magnets have been investigated by Lenz, Jacobi, Müller, and others.

The experiments of Pfaff gave the following results:

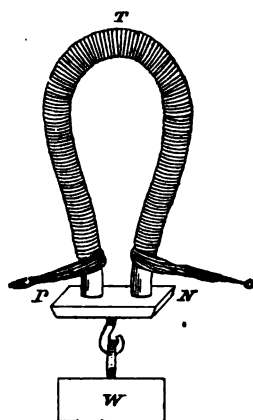
1. The amount of suspensive force is immediately dependent on the intensity of the electric current which circulates about the iron; and the intensity of the magnetism excited in the soft iron is exactly proportional to that of the electric current.
2. The intensity of the current continuing the same, the magnet's suspensive power increases with the number of turns made by the wire; or, the total effect of all the coils is equal to the sum of their effects if taken singly.
3. The attractive force of an electro-magnet increases as the mass of the iron composing it, and this increase is proportional to the diameter of the iron cylinder, their lengths being equal.
4. The purer and softer the iron and the more homogeneous the mass, the stronger the magnetism it is capable of receiving.
5. The form of the iron influences its suspensive power. Cylinders carry greater weights than rectangular bars; and a hollow cylinder from which a portion has been cut away, so as to form a long horseshoe magnet when viewed in the direction of its axis, but a very short one if taken as to its height, is capable of receiving a very great suspensive force; and lastly, a slight curvature of the polar surface adds considerably to its power.

At the moments of magnetization and demagnetization of iron bars, peculiar sounds are produced. These are best observed by resting the end of a long iron bar surrounded with a coil of covered copper wire on a sounding-board; it thus becomes a musical note, which may be heard distinctly over a large room.

By suspending an iron bar so that it could vibrate freely, and circulating the voltaic current by a wire so arranged as not to touch the bar, and breaking and renewing battery contact rapidly, Beatson elicited sounds as loud and distinct as those from a small bell. He ascertained that at the moment the sound is produced the metal undergoes a sudden expansion, and that on interrupting the current a sudden contraction takes place, the expansion and contraction being independent of that produced by the heating power of the current.

The effects are evidently caused by a molecular disturbance of the

Fig. 26.



particles of the metal by the magnetic-inducing influence of the current. This is well shown by an experiment arranged by Grove, in which a glass tube, open at both ends, but protected along its length with a copper jacket, is filled with water, in which is suspended powdered magnetic oxide of iron. On looking through the tube at distant objects, a considerable portion of the light is interrupted by the heterogeneous arrangement of the particles of oxide; but on passing a current through a coil wound round the tube, these particles assume a symmetrical character, and much more light is transmitted. Tyndall refers the lengthening of an iron bar at the moment of magnetization to the effort and partial success of the granules of which the bar is composed to set their longest dimensions parallel to the axis of the bar, in the same manner as iron filings, which are virtually so many little rods of iron, when shaken over a paper screen placed over a large flat magnet, set their longest dimensions in the direction of the magnetic curve.

CHAPTER IV.

MAGNETO-ELECTRICITY, THERMO-MAGNETISM, AND DIA-MAGNETISM.

Magnetism considered as a universal agency—Experiments of Coulomb and Becquerel—Arago's researches—Influence of metallic and other substances on the magnetic needle—Faraday's researches—Magneto-electricity—Thermo-magnetism—Supposed magnetism of light—Faraday's discovery of a new magnetic condition of bodies—Dia-magnetism—General relation of magnetic agency to common matter.

54. We have seen that magnetic substances are said to attract, or are attracted by, either pole of the magnet. Non-magnetic substances neither attract nor are attracted by the magnet. Magnetic substances are said to have polarity when they have directive force, in which case they attract one pole of a magnet and repel the other.

Iron being, with rare exceptions, the only substance in which magnetic properties are powerfully apparent, almost every kind of matter was for a long time considered as non-magnetic; and hence arose an arbitrary classification, assembling the few substances susceptible, together with iron, of being attracted by the magnet, under the head of magnetic bodies, other substances being classified as non-magnetic bodies. It has, however, been made a matter of some question how far all bodies are not to be considered as magnetic bodies—a conclusion which has received very considerable support by the many brilliant discoveries of modern times in this department of science.

Iron is undoubtedly, of all substances, the most universal and powerful as a magnetic body; and when we consider its great dispersion and admixture in a greater or less degree with other substances, there are certainly some grounds for inferring that the attraction of many bodies

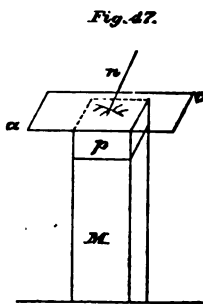
for the magnet may depend on the small quantity of iron they contain; the many experiments, however, made on a large class of bodies essentially differing in their composition, and in several of which the presence of iron could not be well imagined, necessarily led to the conclusion that some other bodies at least, besides iron, must be considered as magnetic substances.

The metal next to iron, which appears to afford the most decided evidence of pure magnetic development, is nickel, which not only attracts and is attracted by the magnet, but is further capable of retaining a distinct polarity. M. Biot determined by a well-executed experiment the comparative directive power of a magnetic needle of pure nickel, and a steel needle of exactly the same dimensions, and found the directive force of the needle of nickel about one-third that of the steel: these needles were 8 inches long, and two-tenths of an inch wide, and weighed about 5 grains. The nickel had been carefully purified by M. Thenard.

Mr. Cavallo found that hammered brass also acquired by hammering a great amount of magnetic force, although every care was taken to free the brass from the presence of iron. This philosopher further found, that several metals were also attracted by the magnet. Rhodium, iridium, and antimony, when heated, also evinced this property. Many non-metallic minerals and earths have been found attractive of the magnet, more especially after being exposed to the action of fire.

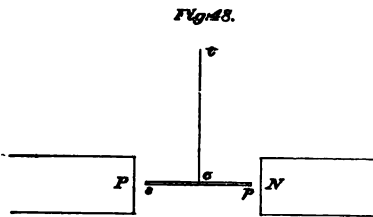
55. We are indebted to Professor Wheatstone for a delicate and very elegant means of observing such magnetic forces.

EXPERIMENT 39.—If a fine short sewing-needle, *n*, Fig. 47, the eye end being broken off, rest upon its point, *p*, on the polar surface, *p*, of a very powerful magnet, *M*, it will generally take a position inclined to the surface; but a locality may generally be found in which the needle will stand nearly vertical. This point may be ascertained by placing a piece of unglazed paper, *a c*, between the needle and point and the steel, and moving it about until the vertical position of the needle is obtained. If we elevate the paper and needle above the magnet to the greatest distance at which the needle will remain vertical, it becomes to the last degree sensitive of magnetic force, so that by bringing such specimens of the metals we have named as have the least magnetic power, or containing iron, near the upper extremity of the needle, the needle will be observed to incline and sway about as it were on its point under their influence. The magnetism of nickel, cobalt, rhodium, iridium, hammered brass, and other substances, easily becomes apparent in this way.



56. About the year 1802, Coulomb endeavored to determine the question of a "universal magnetism" by delicately suspending fine needles of various substances between the poles of opposed compound magnets (19), and causing them to oscillate, first, beyond the influence of the

magnetic poles, and then immediately between them: the result, as stated by Coulomb, was, that the time of the oscillations became sensibly decreased by the influence of the magnetic poles, and all the substances tried finally settled in the direction of the poles. The annexed Fig. 48



represents the form of Coulomb's celebrated experiment, in which $P N$ are the poles of two powerful compound magnets (19), $p s$ a small needle of any given substance, about four-tenths of an inch long and one-fiftieth of an inch thick, suspended between the magnet by a silk fiber, $t c$, attached to a small

paper ring, c , in which the needle $p s$ was allowed to rest. The needle $p s$ and the poles $P N$ were covered by a glass receiver to shield the needle from the air; by raising the rod at t , through the neck of the receiver, and to which the suspension thread $t c$ and needle $p s$ were attached, it became easy to place the needle, when required, beyond the influence of the magnetic poles. It appeared from these results that all bodies either contained indefinitely small quantities of iron or were otherwise susceptible of ordinary magnetic influence, or finally, that, as suggested by M. Biot, the phenomena depend on some force in nature not hitherto known.

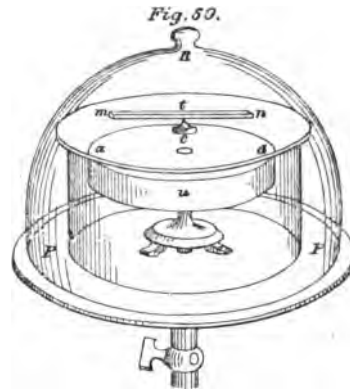
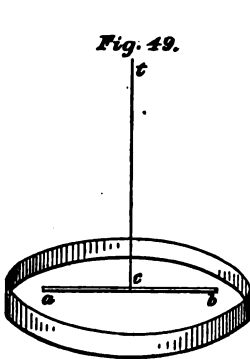
57. With a view of detecting the presence of extremely small portions of iron in various bodies, Coulomb resorted to the method of oscillation; having determined the accelerating force of a known mechanical admixture of iron with a given substance, he found that the action of the poles of the magnet was proportionate to the quantity of iron the admixture contained, and that the presence of any quantity of iron, however small, might be thus determined. M. Haüy sought to render this method still more sensible by deflecting a delicately suspended needle from the meridian by means of a magnetic bar brought within such a distance of the needle, and in the same right line, as would cause the needle to stand nearly perpendicular to the bar—that is, east and west. A needle thus circumstanced is so sensible of magnetic force that a very feeble magnetic action exerted on it by another body will cause it to turn on its center of suspension. M. Haüy called this the process of “double magnetism.”

Following out this process, Becquerel, finding that a needle of soft iron might be substituted for the magnetic needle employed by M. Haüy, proceeded to submit to experiment several oxides of iron, which he inclosed in a thin paper case, suspended in various positions at a given distance from the pole of a common magnetic bar; and he found in certain instances, with an admixture of the second and third oxide of iron, that the paper case, instead of taking the line of the pole of the bar, as would be the result with a needle of soft iron, and with the magnet placed beyond it in the same given position, that the case stood at right angles to the line of the poles, from which he inferred that the

line of magnetism was transverse to the direction of the poles. On repeating Coulomb's previous experiment Fig. 48 (56), with needles of white wood and gum lac suspended very near the magnets, but *above* the interval between the poles, he obtained a similar result; the needles, instead of settling in the line of the poles as observed by Coulomb, stood transverse to that line.

58. About the year 1829, M. Arago made very considerable advances in this interesting physical question by one of those happy perceptions peculiar to great philosophical minds. M. Arago thought of observing the oscillations of a magnetic needle (6), (21), when placed in the vicinity of various substances, so as to detect thereby any force which such substances might exert on it; and he arrived at this remarkable fact: that the influence of substances generally on a vibrating magnetic bar was such as to bring the needle more or less rapidly to rest by diminishing the amplitude of the oscillations without at all affecting the time in which an oscillation was performed. Metallic substances were found to have the greatest influence on the needle. They all brought the needle to rest more or less rapidly.

EXPERIMENT 40.—A small magnetic bar, *a b*, Fig. 49, suspended by

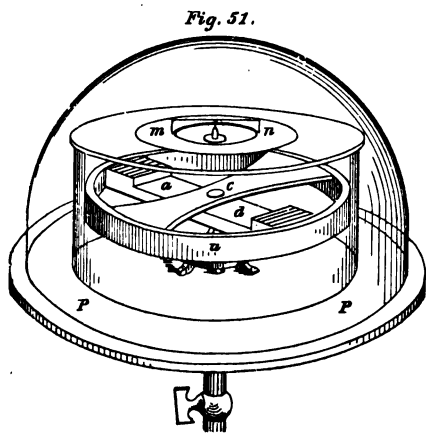


a delicate silk fiber, *t c*, within a ring of copper, *a c b*, is reduced rapidly to rest on being allowed to vibrate freely across the meridian; *e. g.*, a small bar, *a b*, about $4\frac{1}{2}$ inches long, three-tenths of an inch wide, and one-tenth thick, was suspended by a fine fiber within a copper ring, about one-eighth of an inch thick and an inch deep; the whole was covered by a glass receiver, and the air removed by an air-pump. The bar being drawn aside 45° from the meridian, was allowed to vibrate, and the number of vibrations taken between 45° and 10° . The same being determined when the copper ring was removed, it was found that in free space the bar performed 420 oscillations before it reached an arc of 10° ; whereas when surrounded by the copper ring, with the poles very near the inner surface, only 14 oscillations were performed before the bar oscillated in an arc of 10° , thereby showing the great influence of the metal. In a ring of wood the oscillations were reduced from 420 to about 300. This force of metallic bodies on the magnetic needle is so

great that plates of copper and other metals made to revolve rapidly in a horizontal plane, and immediately under a suspended magnetic bar, drag the needle round and finally set it in rapid motion—a result which invariably ensues with the bodies completely sheltered from currents of air and placed under glass screens in the best vacuum which can be produced by a common air-pump. There are several methods of exhibiting this curious fact: a plate of copper or some other metal is set in rapid movement under a magnetic needle, or conversely a magnetic bar is rotated under metallic plates lightly suspended. The rotation may be produced and continued either by a train of wheels and a descending weight, or otherwise by a powerful initial impulse, as in the method of spinning a common humming-top. The following are some of the experiments:

EXPERIMENT 41.—A plate of copper *a d*, about 5 or 6 inches in diameter and one-eighth of an inch in thickness, is soldered to a ring of lead, *a u d*, about 1 inch deep turned true in a lathe, and delicately poised on a point, *c*, resting on an agate center; a screen of flat glass, *a t d*, is placed over the copper disk, and a magnetic bar, *m n*, poised on a fine center, is placed centrally on the screen; a silk line having been wound many times round the ring of lead *u*, previously to covering the disk, is attached to a train of wheels, and the line run rapidly off the circumference *a u d*; the whole is, by this contrivance, set into a smooth and very rapid motion of from 700 to 800 rotations in a minute, which will continue for a considerable time with a slow retardation: when the metal has been thus set in motion, and the bodies are effectually screened from each other in the way just stated, if the center *c* be previously secured to the plate of an air-pump, *P P*, we may cover the whole with a glass receiver, *P R P*, and withdraw the air; in a short time the magnetic bar *m n* will be observed to spin round with immense rapidity.

EXPERIMENT 42.—For exhibiting the rotation of a metallic plate by the influence of a magnet, we may employ a hardened and magnetized circular steel plate mounted on a ring of lead, as in the former case, or a small set of magnetic bars, *a d*, Fig. 51, set and poised in a ring of lead, *u*, and mounted on a center, *c*, as before, the plate of copper, *m n*, or other metal, is poised on a fine point, and placed immediately over this on a glass screen, rapid motion being imparted to the magnetic plate or magnet, *a d*, as before; the copper plate above

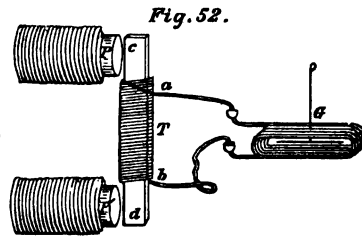


begins to rotate, and finally revolves rapidly with the magnet.

59. When these novel effects were first obtained, they were supposed to arise from the latent magnetism of matter generally, by which certain small temporary forces were induced in bodies in the common way of ordinary magnetic induction (33), and that hence we had additional evidence of a universal magnetism. Arago, however, before attempting any explanation of the cause of the phenomena, sought, with his usual penetration, to resolve the force in operation into certain relative components, and he found amongst these a vertical repulsive force by which a long needle, suspended and poised over the revolving disk from the arm of a delicate balance, became thrown up. A second component consisted of a horizontal force, by which the bar over the disk rotated; and a third was observed to act in the direction of the radius of the disk, so that a dipping needle, or needles of inclination (29), became in certain points repulsed from the center of the disk, in other points, drawn toward it. Taking these phenomena into consideration, together with the total absence of all sensible attraction between the magnetic needle and the copper plate when at rest, Arago concluded that the force in operation was not an ordinary magnetic force, but arose out of some peculiar and unknown agency to be yet investigated. The important fact that only the amplitude, not the time of the vibrations of the magnetic needle, is affected by the presence of a metallic or other substance, would go far in support of this opinion, since in every case in which an oscillating needle is exposed to the action of a magnetic substance, the time of its vibrations is changed.

60. About the period of these researches, Faraday, considering that as magnetism could be derived from the influence of ordinary electrical currents the converse of this proposition should be also true, and that magnetism should be producible by voltaic currents, sought by the operation of powerful magnets of helices of wire (51), to develop currents of electricity throughout the wire; and he succeeded in obtaining such currents for a small portion of time sufficiently strong to affect the the electro-magnetic multiplier (46), so strong as even to produce the ordinary electrical spark, and in the following way:

EXPERIMENT 43.—A case of pasteboard, T, Fig. 52, was surrounded by several superposed helices of copper wire, *a b*, about one-twentieth of an inch in diameter, and cut off from each other by silk or some bad-conducting matter; all the extremities were collected at each end, *a* and *b*, and connected with an electro-magnetic multiplier G; a cylinder, *c d*, of very soft iron was placed within the pasteboard case, T, that is, within the spirals *a b*, and then the extremities *c d* of the cylinder were brought into contact with the opposite poles P P' of two powerful magnetic bars, or an electro-horse-shoe magnet (53). A brief but decided electrical current rushed



through the spirals, and the needle of the galvanometer became deflected in a given direction. Here the action apparently ceased, but, on breaking the contact with the magnetic bars, an opposite rush of electricity was induced in the wire, and the needle became deflected in the reverse direction. This effect, but in a less degree, was found to ensue by contact with the helix only, without the iron cylinder. In this case, however, a very powerful compound magnetic battery is requisite.

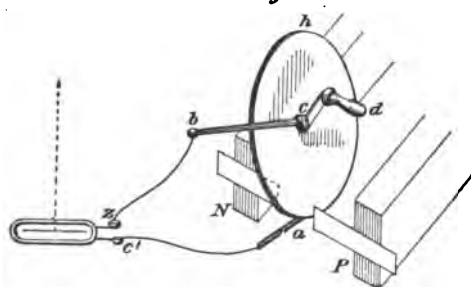
EXPERIMENT 44.—When a piece of copper plate was wrapped once round the iron cylinder *cd*, with interposed paper to prevent metallic communication, and the edges of the plate connected with two wires passing to the electro-magnetic multiplier *G*, Fig. 52, then, on making contact with the poles of the magnetic bars, the needle was deflected as before.

61. This effect has been termed magneto-electrical induction, and the current itself, magneto-electricity. The influence of the magnet in this case is considered as analogous in its mode of action to that of a wire carrying an electrical current on a similar secondary or passive wire placed very near it, and in which momentary electrical currents, sensible to the multiplier, are induced by the action of the primary wire, but in a reverse direction—an effect which has been termed volta-electric induction.

62. The inductive influence of the common magnetic poles on an heliacal or convoluted wire is also traceable in drawing a long slip or plate of metal through a small opening between them. Currents in this case also are induced in the metal, which flow at right angles to the direction of the motion of the plate, an effect which may be rendered extremely sensible in the following way.

EXPERIMENT 45.—Mount a circular copper disk, *abhd*, Fig. 53, about

Fig. 53.



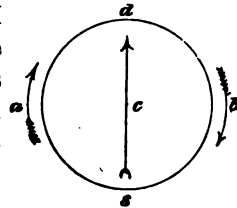
a foot in diameter and one-fifth of an inch thick, on an axis, *c*, in any convenient frame, and place two powerful magnetic poles *P N* on each side of its inferior edge *a*. Let a stout grooved wire, *a*, bearing against the edge of the circumference of the disk, and immediately between the magnets, be connect-

ed with one of the cups of the coil of the multiplier *c'*, and a similar wire, *bc*, resting on the axis *c* of the plate, be made to communicate with the other cup of the multiplier; let the copper disk be now turned round between the poles of the magnets *P N*; immediately this is done, the needle of the multiplier is deflected, currents are induced in the disk, either flowing from the circumference at *a* to the center *c*, or from the center *c* to the circumference at *a* and its vicinity, according to the posi-

tion of the magnetic poles and the direction in which the plate is turned; these currents, returning between c and a through the coils of the multiplier (which may be considered as a uniting wire) (40), deflect the needle from its position within the coil. If we suppose the disk to revolve directly in the line of the meridian, that is, towards the north, and the north pole P of the magnet to be on the right hand, then the current flows from the center c to the circumference a and the neighboring parts, and back again by the multiplier to the center. If we reverse the motion, or change the poles of the magnets, then we reverse the direction of these currents.

63. It appears from these and many other similar experiments, that whenever any metallic substance is passed before a single pole, or between the opposite poles of a magnet, whether a metallic plate, slip, or even a long metallic wire, currents are induced transverse to the direction of the motion of the metal. Here then we have a fair explanation of this new species of force which Arago considered to exist in his experiments with a revolving disk and magnetic needle (58), and which it must be allowed differ materially from cases of ordinary magnetic action. If in the revolving disk (58), Fig. 50, we take one of the radii in the direction of the magnetic meridian—suppose the radius $c d$ in the annexed Fig. 54, c being the south, and d the north extremity, and imagine that by the motion of the disk $a d b s$, in the direction of the arrows $a b$,

Fig. 54.



a current of electricity sets from c to d , immediately under the magnetic needle $s d$, then, by (c) Table I (41), the north pole of the needle d moves to the right hand, and the south pole s to the left, that is to say, in the direction of the motion of the disk. Now we may consider the disk as made up of a succession of radii indefinitely near each other, and hence a continued current is produced immediately under the needle, which returns in remote portions of the disk, and by which the needle is first deflected and finally set into rapid motion; and thus we are enabled (41) to explain every circumstance connected with these interesting phenomena. Similar reasoning applies to the case of the rotation of a magnet under a movable disk, it being evidently of no moment whether we suppose the disk in motion under the magnet, or the magnet in motion under the disk; in either case the force is reciprocal (44).

64. We may consider the tangential force in these cases to be resolved into two component forces, one parallel to the plane of rotation and the other perpendicular to it; the first causes the circular motion, the last would be a repulsive force, as observed by Faraday, and is probably the particular force specified by M. Arago (59); and since without the motion of either the disk or the needle the electrical currents would not be induced, it further follows that no attractive or other force is observable when the bodies are at rest.

If we suppose the copper disk, Fig. 50, to be fixed, and the needle m n to be in oscillation over it, or that the needle be in oscillation within a ring of metal, Fig. 49, there would necessarily arise a dragging or retarding force upon the needle, by which the extent of the vibration would be continually abridged, without the time of the vibration being affected; and hence the needle would be rapidly brought to rest; for, since the disk cannot move and follow the oscillation, it must necessarily fetter the movement of the needle.

65. When a thick plate of iron is interposed between a rotatory disk and a magnetic bar revolving over it, Fig. 50, the motion is completely arrested; but mere plates of other substances were not observed to exert any influence in this way as a screen. By subsequent researches, however, it was found that mass was requisite to this effect. Thus a mass of copper about 3 inches thick and a foot square, being interposed between a rotatory magnetic disk and a thin disk of tinned iron poised on a center immediately over it, completely arrested the motion impressed on the iron. Silver, zinc, and other metals exert a similar influence, when employed in masses of sufficient magnitude to compensate for their respective magneto-electrical energies. It is probable that this screening effect depends on similar principles to those already explained (38).

66. We may obtain a comparative numerical value of the magneto-electric energies of various substances by the following formula,

$$\left(\frac{a}{b} - 1\right)r,$$

in which a represents the number of vibrations of a magnetic needle in free space, taken between given arcs of amplitude, as, for example, between 45° and 10° ; b , the number of vibrations within the same limit under the influence of any particular substance, r being unity, as representing a constantly retarding force. Thus, if in free space (Experiment 40) a delicately suspended bar performs 420 oscillations before the arc of vibration is reduced from 45° to 10° , and that under the influence of two given and different metallic substances, the vibrations within the same limits are 30 and 20 respectively; then the energy of the one is represented by

$$\left(\frac{420}{30} - 1\right)r,$$

and the other by

$$\left(\frac{420}{20} - 1\right)r,$$

that is to say, they are to each other as 13 : 20.*

* A magnetic bar or needle vibrating under the influence of any given substance (Example 54) may be conceived to be reduced to rest by two retarding forces, one which would reduce the bar to rest when vibrating alone, and the other emanating from the substance itself; call the first r and the latter R , then we have for the com-

67. By a series of experiments it appears that the magneto-electric energy of bodies is directly as the mass of the substance within the limit of the magnetic influence, and inversely proportional to the square of the distance of any particle from the magnetic pole. As a consequence of this, it was found that the influence of the same substance on the magnetic needle is directly as its density. The following table exhibits the relative energies of the metallic substances subjected to experiment and calculated by the formula just given (66):

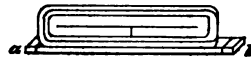
TABLE III.—*Magneto-electric energy of metals.*

Cast bismuth.....	0.45
Fluid mercury	1
Cast antimony	1.3
Solid mercury.....	2
Cast lead	3.7
Cast tin	6.9
Cast zinc.....	10
Cast gold	16
Cast copper	20
Rolled copper	29
Rolled silver	39

68. A disturbance of the equilibrium of temperature is another source of electrical currents in metallic substances, and which flow between the heated and cooled parts, so as to deflect the magnetic needle, as in the previous experiment.

EXPERIMENT 46.—Let the extremities of a rectangular coil of insulated wire, Fig. 55, be attached to the opposite ends of a bar of bismuth, a b , and a delicate needle suspended within the coil. Then, if heat be applied to one extremity a of the bar, the needle is immediately deflected; and this action is augmented if ice or other cooling substances be applied at the opposite extremity b .

Fig. 55.



When two different metals are united by soldering them together, then, by heating the metals at the point of junction, and cooling the more distant portions, this current action is very greatly increased. The most powerful combination appears to be that of antimony and bismuth.

bined or total force $r + R$. Let a be the number of oscillations in free space, and b the oscillations under the influence of any given substance; then, since the number of oscillations may be taken as inversely proportional to the retarding forces, we have $a : b :: r + R : r$, or $a r = b (r + R)$. From whence we derive

$$R = \frac{ar - br}{b} = \frac{a - b}{b} \times r = \left(\frac{a}{b} - 1 \right) r;$$

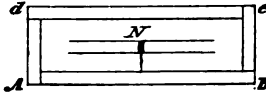
but r being a constant force, may be taken as unity; hence the variable force of the different substances on the needle may be represented by

$$\frac{a}{b} - 1;$$

so that in dividing the number of oscillations in free space by the number under the influence of any given body, and subtracting unity from the quotient, we have a numerical value of the retarding force of the body.

EXPERIMENT 47.—Solder together, at right angles to each other, four bars of antimony and bismuth, A d d c and A B B c, Fig. 56, so as to unite two combinations

Fig. 56.



of such bars into a rectangular frame, A c. Place an astatic needle N (29) within the rectangle, and apply heat to one of the junctions, A, by means of a spirit-lamp, and keep the opposite angle c, cool by means of ether dropped on a thin fold of muslin wrapped round the metallic joint. The needle N is immediately deflected from its position and tends to stand at right angles to the rectangle, as in other cases of deflection (40).

The intensity of these thermo-electrical currents increases with the temperature up to a certain point, about 120° of Fahrenheit's scale; after this, that is, probably, when the heat begins to pervade the metal more equably, the intensity of the current in most instances declines.

Experiments have shown that the thermo-electric properties of metals have no connection with their voltaic relations, or with their powers of conducting heat or electricity; neither do they accord with their specific gravities or atomic weights. In forming a thermo-electric series it is desirable to combine an extreme *positive* with an extreme *negative* metal. The following series was arranged by Professor Cumming. When any of these metals are heated at their point of junction, electrical currents are developed in such a manner that each metal becomes positive to all below and negative to all above it on the list, and the reverse order is observed if the point of junction be cooled:

Galena.	Cobalt.	Gold.	Charcoal.
Bismuth.	Manganese.	Copper.	Plumbago.
Mercury. }	Tin.	Silver.	Iron.
Nickel. }	Lead.	Zinc.	Arsenic.
Platinum.	Brass.	Cadmium.	Antimony.
Palladium.	Rhodium.		

The following thermo-electric order and energy of various bodies for temperatures usually ranging about between 46° and 100° has been published by Matthiessen (Phil. Trans., 1858). In the table the electro-motive force of the thermo-current excited between silver and copper is taken as equal to 1, the current passing from the silver to the copper at the heated end. The numbers represent the force of the current between silver and each metal in succession, heated to the same point. The asterisks denote that the metal by which it is placed was supposed to be chemically pure:

Thermo-electric order of metals, &c., according to Matthiessen.

Bismuth, commercial pressed wire	35.81
*Bismuth, pressed wire	32.91
*Bismuth, cast	24.96

Crystallized bismuth, axial.....	24.59
Crystallized bismuth, equatorial.....	17.17
Cobalt.....	8.97
Potassium.....	5.49
Nickel.....	5.02
Palladium.....	3.56
Sodium.....	3.09
*Mercury.....	2.524
Aluminum.....	1.283
Magnesium.....	1.175
*Lead, pressed wire.....	1.029
*Tin, pressed wire.....	1.006
Copper wire.....	1.000
Platinum.....	0.723
Iridium.....	0.163
*Antimony, pressed wire.....	0.036
*Silver.....	0.000
Gas coke, hard.....	0.057
*Zinc, pressed wire.....	0.208
*Copper, voltaic.....	0.244
*Cadmium.....	0.322
Antimony, pressed wire.....	1.897
Strontium.....	2.028
Lithium.....	3.768
*Arsenic.....	3.828
Calcium.....	4.260
Iron, piano wire.....	5.218
Antimony, axial.....	6.965
Antimony, equatorial.....	9.435
Alloy; 12 bismuth, 1 tin, cast.....	13.670
Alloy; 2 antimony, 1 zinc, cast.....	22.700
*Tellurium.....	179.80
*Selenium.....	290.0

Thermo-piles.—The arrangement by Nobili and Melloni is shown in

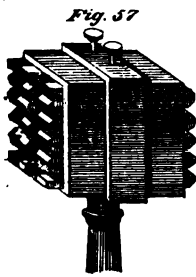
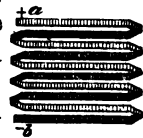


Fig. 57

Figs. 57 and 58. It is composed of a series of small bars of antimony and bismuth, placed parallel side by side, forming one prismatic bundle about $1\frac{1}{4}$ inches long, and somewhat less in diameter.

Fig. 58



The bars of bismuth which succeed alternately to those of antimony are soldered at their extremities to the latter metal, and separated at every other part of their surfaces by some insulating substance, such as silk and paper.

The first and last bars have each a copper wire, which terminates in a peg of the same metal passing through a piece of ivory in a ring; the space between this ring and the elements of the pile is filled with some insulating substance. The loose extremities of the copper wires are connected with the ends of the wire of a galvanometer, which indicates by the motion of the needle any variation in the temperature of the opposite faces of the pile.

Thermo-electricity is characterized by very feeble tension. It can therefore produce feeble chemical action. The battery above described will, however, though on so small a scale, decompose water (feebly), and give small sparks between iron points; will enable an electro-magnet to sustain 2 cwt.; and when substituted for the voltaic battery with a 6-inch spark induction coil, will cause the production of sparks 1 inch long between the terminals of the secondary coil.

69. An opinion has been long entertained by philosophers that, since iron loses its magnetic energy at a very high temperature, and regains it again as the temperature falls, there probably exists a low degree of heat at which all metallic substances would assume a magnetic condition similar to that of iron. This view, however, has not been confirmed by experiment. Faraday, in 1839, reduced the temperature of antimony, bismuth, cobalt, copper, and various other metals below 110° of Fahrenheit's scale, but without developing in these bodies any kind of magnetic power. We have, so far, no evidence of what may be termed the direct magnetism of temperature.

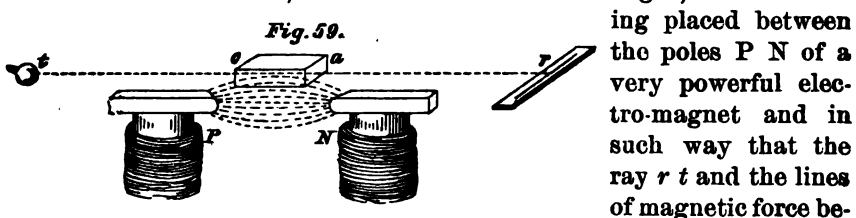
70. Magnetic influence, as a universal agency, has been also extended to light, but with as little eventual confirmation by careful experiments.

71. Faraday found that lines of magnetic force, in passing through certain transparent bodies, so affected their molecules as to impress on them a peculiar magnetic condition quite new to us, and by which a divided ray of light also passing through the body at the same time parallel to the magnetic lines, becomes bent, as it were, in its course, the character of the force impressed on the ray being that of rotation.

72. By lines of magnetic force we are to understand such forces as are exerted between two opposed magnetic poles (28), Figs. 15, 16, 17; they may be either straight or curved.

Any substance through which such forces pass *without* rendering the substance magnetic, after the manner of iron, is termed a dia-magnetic substance; and the peculiar condition impressed upon its molecules by the transmission of the magnetic forces, dia-magnetism.

EXPERIMENT 48.—If a divided and reflected ray of light, rt , Fig. 59, be passed through a cube of heavy glass, ac , about 2 inches square and one-half inch thick, in the direction tr of its length, this cube be-



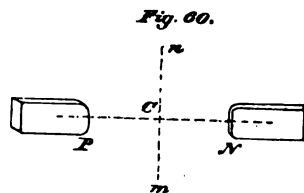
ing placed between the poles $P N$ of a very powerful electro-magnet and in such way that the ray rt and the lines of magnetic force between $P N$ (28) may be nearly parallel to each other; and if previously to sending the current through the coils of the electro-magnet (53) we view the ray through an eye-piece, t , containing a crystalline substance, by means of which we can, in turning round the eye-piece on its axis, cause the image of the flame of the lamp from whence the light first

proceeds to disappear, then, immediately, we send the current through the coils of the electro-magnet, the image of the flame will again reappear, evidently showing that the ray had become bent or turned aside from its first course.*

When the image of the lamp flame has thus been rendered visible, the revolution of the eye-piece to the right or left, more or less, will cause its extinction. If the pole nearest the observer be a north pole, the ray rotates to the right hand; if the poles be changed by reversing the current, the ray rotates to the left hand.

By way of illustration, let a common watch be taken to represent a diamagnetic substance, and suppose the north pole of a magnet applied to its face, and the south pole to its back, and a polarized ray of light to pass at the same time through the watch, from the back to the face, towards the observer; then the course of the hands of the watch is the direction, in this case, in which the ray is caused to rotate by the influence of the lines of magnetic force. A great variety of transparent bodies, such as flint glass, acids, alkalies, fixed oils, water, alcohol, ether, exhibit this curious phenomenon; but rock crystal, Iceland spar, and substances possessing the power of double refraction, have no such effect.

73. When these substances which we have termed diamagnetic (72), and which comprise a very extensive class of bodies, are delicately suspended between the poles of a powerful electro-magnet, they invariably stand transverse to the magnetic lines of force. Let, for example, P N, Fig. 60, be the terminating poles of an extremely powerful electro-magnet, as in Fig. 59. We may term the intermediate space *c*, between these poles, the magnetic



* A ray of light, in passing through certain crystalline mineral substances, becomes split, as it were, into two portions by some peculiar property of such bodies, thus giving origin to two distinct images. If these rays be now caused to pass through a second similar crystalline body, placed in a particular position, they are subjected to a still further division, and each ray undergoes a certain physical change; this physical change has been termed polarization. If we take then a fine plate of the tourmaline, for example, cut from the mineral in a plane parallel to the axis of the prism, we may perceive a candle through it as through a plate of colored glass. If under these circumstances we interpose a second similar thin plate of tourmaline between the eye and the first plate, and turn this second plate slowly round upon a horizontal axis, the candle will disappear and reappear at every quarter of a revolution, according as the line of section of the two plates coincide or cross each other. If the original ray of light be reflected from a plane mirror at a given angle, and we examine this reflected ray by a single plate of tourmaline in a similar way to the preceding, the same thing occurs as with the two plates—the image of the candle or lamp from which the rays proceed will appear and disappear at every quarter of a revolution. In the experiment above described, a prismatic eye-piece, termed a Nichols' prism, was employed, consisting of a crystalline substance capable of turning aside one of the rays and employing the other free from color and by turning round which, upon a horizontal axis, the image of the flame from the reflected ray could be made to disappear.

field; the line of the poles $P N$, the axial line; and the line $m n$, perpendicular to this and passing through the center of the field, the equatorial line.

EXPERIMENT 49.—Let a bar of heavy glass or any of the substances not magnetic, after the manner of iron, be suspended by a silk fiber, so as to hang in the center c of the magnetic field or space between the poles $P N$, Fig. 60; pass a strong current through the coil; the bar, if previously settled axially in the line $P N$, will now vary from this position and settle in the equatorial line $n c m$.

If the substance be near one of the poles, that is, out of the center c , then on pointing equatorially it is apparently repelled, and this repulsive effect is common to both poles.

Faraday submitted a large number of substances, solid and liquid, to the action of the magnet, the liquids being inclosed in small glass tubes hermetically sealed. The results are given in the following table:

POINTED AXIALLY (MAGNETIC).

Paper.	Sulphate of zinc.
Sealing wax.	Shellac.
Fluor spar.	Silkworm gut.
Peroxide of lead.	Asbestos.
Plumbago.	Vermilion.
China ink.	Tourmaline.
Berlin porcelain.	Charcoal.
Red lead.	

POINTED EQUATORIALLY (DIAMAGNETIC).

Rock crystal.	Sulphuric acid.
Sulphate of lime.	Muriatic acid.
Sulphate of baryta.	Solutions of alkaline and earthy salts.
Sulphate of magnesia.	Glass.
Alum.	Litharge.
Muriate of ammonia.	White arsenic.
Chloride of lead.	Iodine.
Chloride of sodium.	Phosphorus.
Nitrate of potassa.	Sulphur.
Carbonate of soda.	Resin.
Iceland spar.	Spermaceti.
Oxalate of lead.	Caffeine.
Tartrate of potassa and antimony.	Cinchona.
Tartaric acid.	Margaric acid.
Citric acid.	Wax from shellac.
Water.	Olive oil.
Alcohol.	Oil of turpentine.
Ether.	

Sugar.
Starch.
Gum arabic.
Wood.
Ivory.
Dried mutton.
Fresh beef.
Nitric acid.

Jet.
Caoutchouc.
Dried beef.
Fresh blood.
Leather.
Apple.
Bread.

Phosphorus appears to stand at the head of all diamagnetic substances; its pointing may be verified between the poles of a common magnet.

If a man could be suspended between the poles, he would point equatorially, for all the substances of which he is made possess this property.

Various gases, simple and compound, were also examined by Faraday, and the following, in relation to atmospheric air, were proved to be diamagnetic, viz:

Nitrogen, hydrogen (strongly so), carbonic acid, carbonic oxide, nitrous oxide, nitric oxide, olefiant gas, coal gas, sulphurous acid gas, muriatic acid gas, hydriodic acid gas, fluosilicon, ammonia, chlorine, iodine, bromine, and cyanogen.

The most striking circumstances in these experiments were the strongly-marked diamagnetic character of *hydrogen*, and the feeble diamagnetic condition of *oxygen*, standing, as it does in this respect, far apart from all other gaseous substances.

Oxygen, indeed, is a *magnetic* substance, its magnetic force being in proportion to its density. It is, in the air, what iron is in the earth, and is in striking contrast with the nitrogen which dilates it in the atmosphere, which is neither magnetic nor diamagnetic, but, magnetically considered, *zero*.

74. Metallic bodies, as a class, are found to exhibit highly interesting and distinctive characteristics in regard to this new species of force; and the powerful operation of the electro-magnet determines at once whether they are to be considered as magnetic substances or not. If magnetic, they would point axially; if diamagnetic, equatorially (73); if near one of the poles, they would as magnetic bodies be attracted; if diamagnetic they would be repelled. On submitting metallic substances to this test, iron, nickel, cobalt were at once found to be magnetic bodies—they all pointed axially; to these may be perhaps added platinum, palladium, and titanium; all the other metals, antimony, bismuth, copper, gold, &c., were found to stand transverse to the lines of magnetic force, and to be repelled by both poles.

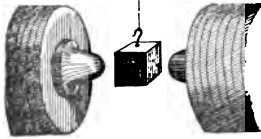
75. The diamagnetic force manifested by different metals varies considerably in degree. Bismuth, which has the least magneto-electric energy of all the metals has the greatest diamagnetic power. Anti-

mony, another metal low in the scale of magneto-electric energy, also exhibits considerable diamagnetic force. It is further remarkable that copper and silver, the highest in the scale of magneto-electric energy have the lowest diamagnetic force.

Copper, in consequence probably of its excellent conducting power for electric currents, exhibits some remarkable phenomena. When a mass of copper is suspended between the poles of a powerful electro-magnet, it first advances towards the axial line, as if it were magnetic; it then suddenly stops, and takes up a new position, from which it can only be removed by the application of some force. Even when swinging with considerable momentum, it can be caught up and retained at will.

In order to form a good idea of the arresting power of these induced currents, let a lump of solid copper, approaching to the globular or cubical form, weighing from a quarter to a half pound, be suspended by a long thread; let a rapid rotation be given to it, and then let it be

Fig. 61



introduced into the magnetic field of a powerful electro-magnet, as shown in Fig. 61. Its motion will be instantly stopped, and on trying further to spin it whilst in the field, it will be found impossible. Or let a disk of copper be set in rapid rotation, and then suddenly introduced into the magnetic field; its rotation will

be instantly suspended.

76. On submitting magnetic and diamagnetic metals to the influence of heat, a decisive difference is still manifest between them. The decidedly magnetic metals, iron and nickel, still point axially and are attracted by the magnet, even when they are heated to such an extent as to annihilate their influence on common artificial magnets; hence these metals are not thus far reducible to a pure diamagnetic condition. Such facts, therefore, are subversive of the opinion (69) that every metallic substance would probably assume a magnetic condition similar to iron if subjected to very low temperatures.

77. Upon a review of the whole course of inquiry from the time of Coulomb's experiments in 1800 to the present day, we are driven to the conclusion that all matter is not susceptible of ordinary magnetism after the manner of iron; that the class of what may be termed magnetic bodies is in this sense very limited, being confined principally to iron, nickel, and cobalt, to which we may add, perhaps, although with a less degree of certainty, palladium, platinum, and titanium. On the other hand, by the discovery of diamagnetic action, the question of universal magnetism becomes placed in a new and very different light. In this case we arrive at the existence of magnetic forces the very opposite of those existing in common magnetic bodies; the first lead to attraction, the latter to repulsion; yet we may fairly conclude that all matter is susceptible of magnetic influence under one or the other of these forms,

that is, either magnetically after the manner of iron, or diamagnetically after the manner of bismuth. In this sense magnetism may be considered as a universal agency. Instead, therefore, of associating bodies under the two classes of magnetic and nonmagnetic bodies, we should distinguish them as magnetic or diamagnetic bodies, and between which there is evidently a definite and striking contrast.

The following order of metallic substances in the scale of universal magnetic force has been derived from Faraday's papers, and, although open to future correction, it is still extremely useful in the way of reference:

MAGNETIC.		DIAMAGNETIC.		
Iron.	Cerium.	Bismuth.	Mercury.	Arsenic.
Nickel.	Titanium.	Antimony.	Lead.	Uranium.
Cobalt.	Palladium.	Zinc.	Silver.	Rhodium.
Manganese.	Platinum.	Tin.	Copper.	Iridium.
Chromium.	Osmium.	Cadmium.	Gold.	Tungsten.
		Sodium.		

0

The scale here, as in the classification of electrics and conductors, runs through neutrality from two extremes: The zero point is to be taken as the condition of indifference to either magnetic force, viz, attraction or repulsion; the farther any metal stands from this point, the more perfect it is of its class.

CHAPTER V.

MAGNETIC INSTRUMENTS, THEIR CONSTRUCTION AND USE.

Artificial magnets—Conversion of iron into steel—Temperament—Various processes of magnetizing—Compound magnets—Magnetic machines—Magnetoscopes and magnetometers—The compass—Various instruments for determining and measuring the hourly changes and declination of the vertical and horizontal needles.

78. The extensive application and importance of magnetism to practical purposes has necessarily led to the construction of a great variety of magnetical instruments. These may be separated into the following classes:

1. Instruments for the accumulation and development of magnetic power.
2. Instruments for detecting the presence, indicating the polarity, and measuring the amount of magnetic force.
3. Instruments for determining the direction and measuring the declination of the horizontal and vertical needles, under a variety of circumstances and conditions, and at any instant.

79. Instruments for accumulation and development of magnetic power consist principally of artificial magnets, simple and compound; com-

binations of compound magnets, termed magnetic machines; and the electro-magnetic spiral.

We have seen that when a mass of iron is applied to the pole of a magnet it becomes powerfully magnetic; the susceptibility, however, of this excitation is less in hard and brittle pieces of iron or steel than in pieces which have been softened by heat. Hard steel, however, possesses, on the contrary, as before observed, a greater retentive power. The magnetism developed in a piece of soft iron, T, Fig. 23, vanishes, or nearly so, directly we remove the iron from contact with the magnet; whereas in substituting a piece of very hard steel, although requiring a higher degree of power for the development of its magnetic energy, we find the magnetism induced in the steel permanent. The magnetic susceptibility and the retentive power are consequently in some inverse proportion to each other. As a first or leading principle, therefore, in the production of magnetic machines, we must seek to obtain the greatest amount of susceptibility consistent with a high retentive power in the steel.

80. We have already described (19) the principal kinds and forms of artificial magnets. These we have found to consist of straight or curved bars of hard steel in which magnetism has been excited by the aid of the natural or other magnets. Now, the degree of force which can be thus produced in bars of steel will be further dependent on the proportion of the surface of the bar as compared with its bulk, all other things being equal. A thin steel plate, for example, may have a much higher degree of *proportionate* magnetic power excited in it than the same quantity of the like steel disposed under a more concentrated form, a result probably dependent on the fact that the magnetic excitation does not reach far beneath the surface (27). Dr. Ingenhous constructed a small magnet of several laminae of magnetized steel firmly pressed together, which he found would sustain 150 times its own weight—a force quite unknown in a single bar of the same dimensions.

81. The best relative dimensions, however, for magnetic bars for general purposes will in some degree vary with the length of the bar and the particular experimental object in view. Cavello recommends, for bars of about five inches in length, that the breadth be one-tenth part of the length, and the thickness one-half the breadth. Canton gave to such bars a breadth of about the one-eleventh part of the length, and a thickness rather less than one third the breadth. Coulomb in his compound magnets, constructed of bars 21 inches long, made their breadth about the one thirty-fifth part of their length, and the thickness one-third the breadth. In the more early experiments by Dr. Gowan Knight the breadth of his magnetic bars was from one-twelfth to one-fifteenth their length, and the thickness one-half the width. For bars of about 2 feet to 30 inches long, the breadth may be about the one-twentieth of the length, and the thickness something more than one-third the breadth. Bars intended for magnets of the horseshoe form (19), Fig. 8, may have

a greater length in proportion to their width than ordinary straight bars.

82. Another great point which we have to consider in the construction of artificial magnets and magnetic machines is the kind and quality of the steel, together with the degree of hardness or temperament to which it has been subjected.

When pure malleable bar iron has been slowly and for a long time heated in a closed furnace, in contact with pulverized charcoal, and subsequently allowed to cool gradually for a space of several days, the texture of the metal becomes changed; it loses much of its ductility and malleability, but gains in hardness and elasticity; it has united with a certain portion of carbon; and has been converted into what we call steel.

83. Steel, when suddenly cooled from a high point of temperature, becomes extremely hard and brittle; hammering will also harden steel very considerably; but the most effective method of hardening steel bars intended for artificial magnets is to raise the temperature of the bar to a bright red or even white heat, and then plunge it into cold-water brine, or some other cold liquid, such as oil. Steel thus treated resists the action of a file, and may be made to scratch glass like the diamond.

84. After being thus hardened, steel may be again softened to any required degree, by the process called tempering, which consists in again exposing it to heat on a plate of red-hot iron. As the heat begins to permeate the metal, the surface will be observed to pass through successive changes of color. First, it will appear to assume a red or purple tint; then a yellow or straw color; this gradually deepens and changes to a light blue; we have then a deep blue; finally the steel becomes red-hot.

We are enabled by these various tints to estimate the degree of hardness retained by the steel at any moment, and may hence, by its removal from the iron at that moment, obtain the precise degree of hardness we require. When we perceive the straw color, the steel will have become a little softened; it is then in a fit state for certain tools, such as drills; this point has been termed "drill temper." When the color has changed to a blue, it is then in a fit state for springs of various kinds; this point has been termed "spring temper." We may therefore, by a little practice, temper steel to any required point.

85. The process of converting iron into steel, and its subsequent treatment, has given origin to several different qualities and kinds of steel, all of which have received some distinguishing term.

During the first process of cementation, with charcoal, the surface of the iron frequently becomes blistered by the heat. Bars in this state constitute what is called "blistered steel"; these bars of blistered steel, when exposed again to heat, doubled, welded together, and again drawn out, produce what is termed "shear steel," of which kind we have the

single and double shear steel, according to the extent of the process of conversion.

When blistered or unrefined steel is fused in a crucible with a little charcoal or black oxide of manganese, in a wind furnace, it may readily be cast into ingots or bars; this is denominated "cast steel." Thus treated, the steel acquires a more uniform texture and a closer grain, and is harder or softer according to the quantity of the flux employed; when subjected to the action of the hammer, the texture becomes still more compact, constituting hammered cast steel, one of the most valuable forms of steel as yet obtained.

86. Of these different kinds of steel, the hammered ingot steel, made from very good Swedish iron, smelted with wood charcoal of the first quality, may be considered as being well adapted to the purposes of artificial magnets. We are still, however, open to accidental varieties of quality almost impossible to avoid. If the steel, when fractured, exhibits a uniform and small silvery granulated appearance, it will be found, on being properly tempered, susceptible of a high degree of magnetic development. It is always, however, difficult to furnish a universal reply to the question—what is the best kind of steel for magnets, and what degree of temper or hardness should be given to it? The Rev. Dr. Scoresby, to whose unwearied labors in this department of science we are indebted for a most complete and extensive series of experiments and investigations relative to this question, gives the following general deductions:

For straight bar magnets of a massive kind, the best cast steel, made quite hard, should be employed.

For compound magnets, constructed of thin plates of what is called "steel husk," the best cast steel hardened to the greatest possible degree by means of oil.

For single horseshoe magnets, also the best cast steel, tempered from file hardness at about 550°, or shear steel a little reduced.

For compound horseshoe magnets, cast steel tempered at from 480° to 500° Fah., or shear steel rendered perfectly hard.

The limits of the degree of hardness the most effective for all practical purposes are comprised between the brittle hardness of files and that of elastic spring temper.

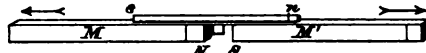
87. Coulomb employed a kind of steel termed *d'acier timbré à sept étoiles*, the bars being tempered at a cherry-red heat. M. Biot, recommends the bars to be first made as hard and brittle as possible, in which case they will be frequently warped and distorted; then to let them down to a temper indicated by the first shade of yellow, at which point they may be set straight with a hammer.*

* In giving steel bars the precise degree of hardness required, it is desirable to let them down from extreme hardness, as recommended by Biot: great uncertainty often arises in the tempering of bars, in the common method of plunging them into cold water at low degrees of heat; thin plates may be rendered quite brittle, whilst thick bars are often but slightly acted on.

METHODS OF COMMUNICATING MAGNETISM TO STEEL BARS.

88. The first means of imparting magnetism to steel was, as we have already described (16), by contact with the armed lodestone or other magnet. A more efficacious method, however, of magnetizing small needles or bars by simple contact consists in placing the bar or needle between the opposite poles of powerful magnets, as for example in the magnetic field S N, Fig. 16, immediately between the poles S N.

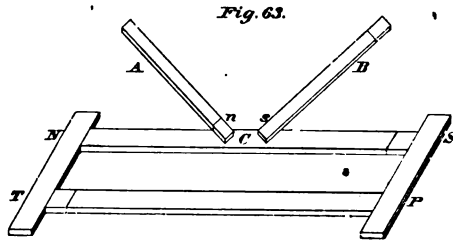
89. We are indebted to Dr. Gowan Knight, F. R. S., a London physician, for the first important step in the communication of magnetism to bars of steel. His method is as follows: Two powerful magnetic bars, M M', Fig. 62, are placed in the same straight line, with their opposite poles, N, S, very near each other; the needle or bar *n s* to be magnetized is laid flat on the surface



of the bars, immediately over the opening N S, between them. If the bar *n s* be a magnetic needle having a cap for suspension, then the cap is allowed to rest between the bars; if the surface be unimpeded by this, the bars M M' may be brought very near each other. Things being thus disposed, the bars M M' are gradually withdrawn in opposite directions, and immediately under the bar *n s*; the result of which operation is, on the principles already explained (17), that each half of the bar *n s* being acted on by opposite polarities, the two magnetic forces resident in it become separated; the pole N of the bar M attracts all the south polarity and repels the north, whilst the pole S of the bar M' attracts all the north polarity and repels the south; hence a final and permanent magnetic state is imparted to the bar *n s*, the position of the poles *n s* being the reverse of the poles N S of the bars (17).

Small needles will become magnetized to saturation by one operation of this kind performed on each of its surfaces; for larger bars two or three or more repetitions are desirable. This method is very effectual, especially for single bars, and there is not, perhaps any better for certain purposes, even at the present day.

90. After this method of Dr. Knight's had become known and practised, M. Du Hamel, member of the Royal Academy of Sciences at Paris, was led, about the year 1749, to a further and still more extensive application of it. Two bars, N S and T P, Fig. 63, required to be magnetized, are laid on a table

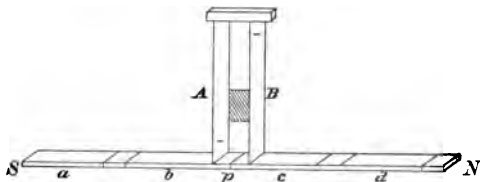


parallel to each other, and their intended opposite poles united by pieces of soft iron, N T, S P, so as to form a closed rectangular parallelogram, as seen in the figure. The opposite poles *n s* of two powerful magnets, A B, either simple or compound, are then applied to the center, C, of one of

the bars, N S, and drawn away from each other in opposite directions, C N, C S, being held all the while at an inclination of about 40° ; this operation is repeated several times; the magnets A B are now either reversed, or their relative positions changed, by turning them round; they are then applied in a similar way to the other bar, P T, so as to bring the poles *s n* opposite to their former position; the same operation is now repeated on the bar T P, and this process is to be further repeated on each surface of the bars T P, N S. M. Du Hamel's method is effective and expeditious; the elementary forces resident in the bars being by the joint operation of the magnets easily separated (14), whilst the union of the opposite poles N T and S P, by soft iron, further tends to increase the effect, by holding together, as it were, the two separated magnetic elements, and thus allowing the exciting magnets A B to operate with more considerable effect.

91. Mr. Michell, of Cambridge, and Mr. Canton, in 1750 or 1751, still further advanced this department of practical magnetism. Michell employed a method which he designated as "the double touch." Several

Fig. 64.

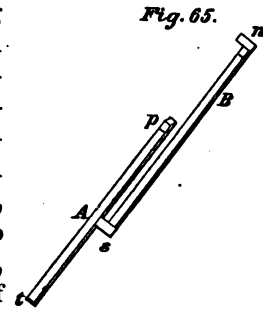


bars, *a b c d*, Fig. 64, to be magnetized are placed in one straight line, the intended opposite polar extremities being in contact; thus the north pole of the bar *a* is placed in contact with the intended south pole of the bar *b*, and so on; the bars being thus disposed, the opposite poles of two powerful magnets, A B, either single or compound, are placed about the center of the series, the opposite poles beneath resting one on each side the center *p*, whilst the distant opposite poles are joined by a piece of soft iron; the system thus formed is now moved backwards and forwards over the line of bars from one end to the other, taking care (17) that the south pole of the system A B applies to the intended opposite pole N of the series of bars S N, and, reciprocally, the north pole to the intended opposite pole, S; the operation is to be repeated several times on each surface of the bars, and the system finally removed at the center, *p*, of the chain. By this operation, the center bars *b c* will be found to have acquired a high magnetic development, the extreme bars *a d* not so high; these are to be now shifted from the extremities to the center, and to be replaced by the center bars *b c*, when the same process is to be repeated. In this experiment, the extreme bars *a d* may be conceived to act as the connecting pieces of soft iron N T, S P, Fig. 63, employed by Du Hamel, and the magnetic elements become separated in precisely the same manner; each polarity, *s n*, of the system A B repels one of the magnetic elements (14) and attracts the other, so that by the reciprocating rectilinear motion one polarity is determined in one direction, and the converse polarity in an

opposite direction. On dislocating the chains of bars, we find each bar a complete magnet.

92. Besides these direct methods we have other processes for obtaining a magnetic development in steel and iron of much practical importance. Marcel, so long since as the year 1722, observed that a bar of iron acquired a temporary magnetic state by position alone (12); and he succeeded in imparting magnetism to a piece of hard steel placed on an anvil, merely by rubbing it with the lower end of a bar of iron about 33 inches long, set upright upon the steel. The temporary magnetic state thus induced by position in the iron bar is such that the lower extremity, in north latitudes, becomes a north pole, and the upper extremity a south pole; and the forces are much increased by placing the bar in the direction of the inclined needle (21); in southern latitudes the reverse of this occurs. Mr. Canton, by an ingenious manipulation of this kind, succeeded in communicating a weak degree of magnetism to steel by means of a common poker and a pair of tongs, and from this magnetized his series of bars to saturation.

93. Savery, in 1730, succeeded in magnetizing bars of hard steel three-quarters of an inch square and 16 inches long, by fitting an armature at each end of one of the bars, and touching the other bars with it whilst held in an inclined position, as represented in the annexed Figure 65. Savery's process was very ingenious, and is worthy of notice. Having fitted two small armatures of iron, *s n*, to one of the bars *B*, he held it in the magnetic meridian in the line of the inclined needle (21); then bringing a second bar, *A*, into a similar position with its marked end, *p*, uppermost, he brought the small armature *s* near its lower end, *t*, and then proceeded to touch the bar throughout its length by gliding the armature *s* nearly to the end *p*. This process being repeated several times, he proceeded to apply the opposite armature *n* in a similar way to the extremity *p*, and then to touch the bar *A* in the reverse direction. Having in this way developed a small degree of magnetism in the bar *A*, he removed the armatures from *B*, and applied them to the weak magnetic bar *A*; he then proceeded to touch *B* in a similar way, taking care to place the marked end of the bars uppermost. By an extension of this process in changing the armatures from bar to bar, and touching the weakest, he obtained a sufficient degree of power to lift a key weighing more than an ounce. From these bars he was enabled to magnetize several others by fixing them in series on a board with reciprocal poles one over the other (91), inclining the board in the direction of the dipping needle. In this position he touched the whole series as before with each of the armatures alternately applied, first in one direction, then in the other; and so by changing the touching bar from time to time,



as the series increased in strength, and allowing each bar to take up a new place, he at length obtained sufficient power to lift one bar with another at their opposite poles. The bars employed in this experiment were of hard steel, 16 inches long and three-quarters of an inch square, and weighed about 3 pounds each. Michell, who adopted Savery's process, placed the steel bar A, Fig. 65, between two large bars of soft iron; by this the effect appears to have been considerably increased.

94. Another method of developing magnetism in steel bars, without the aid of common magnets, consists in subjecting the bar to sharp concussion. This principle was well known to Gilbert so long since as the year 1570. Smiths' tools, such as drills, broaches, &c., which have undergone pressure and motion, are generally magnetic. When a steel punch is driven hard into iron, the punch is not unfrequently rendered magnetic by a single blow.

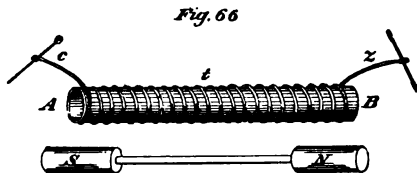
In the "Philosophical Transactions" for 1738 we find an account, by Desaguliers, of iron bars rendered magnetic by striking them sharply against the ground whilst in a vertical position, or otherwise striking them with a hammer when placed in a horizontal position at right angles to the magnetic meridian. Such bars attract and repulse the poles of the needle. According to Du Faye, whose experiments are quoted, it is of no consequence how the bar is struck; all that is required is to impart to the bar a vibratory state whilst in a vertical position.

95. Availing himself of these facts, Scoresby, after a further and critical examination of the subject, succeeded in obtaining magnetic bars of extraordinary power by percussion. In the course of these inquiries a considerable advantage was found to arise by striking the bar whilst resting in a vertical position upon a rod of iron. A cylindrical bar of soft steel, $6\frac{1}{2}$ inches long and one-fourth of an inch diameter, resting on stone and struck with a hammer weighing 12 ounces, could only be made to lift about $6\frac{1}{2}$ grains; whereas when resting on a bar of iron, and struck in a similar way, it lifted 88 grains. Scoresby, in developing magnetism in this way by percussion, first struck a large iron bar in a vertical position, and then laid it on the ground with its acquired south pole towards the north; he then proceeded to strike sharply with a hammer a soft steel bar 30 inches long and an inch square, resting vertically on the south pole of the iron bar. A second similar bar was treated in the same way; then, placing one of these steel bars vertically, he proceeded to strike upon them, as supports, a series of flat bars of soft steel 8 inches long and one-half inch broad, and in a few minutes they had acquired a considerable lifting power.

Large iron and steel bars are not absolutely requisite to the success of this process, common pokers answering the purpose very well.

96. The most powerful method of developing magnetism in iron and steel, without the aid of ordinary magnets, is certainly by means of the electro-magnetic spiral, or by the transmission of electrical currents about the steel.

The kind of apparatus employed for this purpose consists of a stiff pasteboard tube, $A t B$, Fig. 66, about 20 inches long and 2 inches in diameter; a stout copper wire, $c t z$, about one-quarter an inch diameter, covered with silk thread, is coiled closely around this cylinder, terminating in two movable jointed wires, $z c$. The bar, $N S$, to be rendered magnetic is placed between two cores of soft iron $N S$, each about 8 inches in length, and turned to fit the case $A B$, and the whole is placed within the spiral coil $c t z$. This being arranged, contact is made between the terminating wires $c z$ and the plates of four cells of Grove's powerful battery. Supposing the spiral coil to be direct (51), and the current to flow from c to z , so as to descend the coils t next the observer, then the right-hand extremity N of the bar $S N$ will become a north pole (52).



By employing spiral coils of this kind, of sufficient magnitude, any steel bar may be at once magnetized to saturation; small bars and needles will at once receive a maximum degree of power.

97. It is quite essential in every magnetic combination, if we wish to preserve the accumulated force, that the bars or compound magnets be laid with their respective poles reverse to each other and united by soft iron keepers. In the horseshoe magnet the opposed poles are accurately placed by construction; it is only necessary in this case to apply the soft iron keeper.

The magnetic power of a single bar or needle will be effectually and best preserved by placing it in grooved rests of soft iron, fixed to the end of a light iron plate about the same width as the bar; it is thus retained in position and effectually preserved.

Sets of straight bars to be employed for general experimental purposes are usually laid together with reversed poles between small cheeks, fixed in a frame or neat wood tray, lined with red or blue cloth; a short bar of soft iron being placed directly across the dissimilar poles at each end, so as to effectually tie them together magnetically.

98. In combining many bars, either straight or curved, so as to produce accumulative power, we are met by a somewhat serious inconvenience; the mutual repulsion of the similar poles is such that when many bars are set closely together, the proportionate power of the mass as a whole becomes greatly weakened, whilst the magnetism of many of the bars is not only very frequently destroyed, but their polarities become reversed. Scoresby has also fully investigated this question in his "Magnetic Investigations," and from these we derive the following results:

Any single bar or plate has more *proportionate* magnetic power than two such bars or plates conjoined.

A combination of bars or plates is always more powerful than any single bar containing the same quantity of steel in mass.

The *absolute gain* of power by each additional bar diminishes progressively, and hence a limit is attained to the extent of the combination.

99. With a view of avoiding the deterioration in magnetic power, from the repulsion of the similar poles on each other, Scoresby was led, in compound magnets, to interpose disks of wood, cardboard, or some non-magnetic substance, between the extremities of the bars, so as to keep them out of any very close contact: by this arrangement the accumulated power became more fully obtained. When 30 plates of tempered cast steel, 2 feet long, $1\frac{1}{2}$ inch wide, and about $\frac{1}{8}$ of an inch thick, were fully magnetized, and combined and separated by $\frac{1}{2}$ -inch spaces, the resulting compound magnet had at least twice the magnetic energy which the same plates exhibited in contact.

100. The most favorable conditions for the construction of compound magnets are, a similarity of quality and form in the steel, both as to mass and dimensions, and a similarity also in temper; the spacing out or separation of the similar poles by a disk of some intervening non-magnetic substance, and the employment of comparatively thin plates at a high temper, which last appears essential to retentive power, is likewise requisite. Scoresby found that in the construction of a compound magnet of thin plates of steel busk, or other steel plates of commerce, at a spring temper the accumulated power very soon approached a maximum, so that not above 24 plates, in sets from 15 inches to 2 feet in length and one-twentieth of an inch thick, could be usefully combined; whereas, with the same plates rendered very hard, above 192 plates might be effectually combined, and with a result exceeding by five or six times the combined power of thicker bars commonly employed for compound magnets.

The temperament of bars, however, for combinations of the horseshoe form, appears to admit of considerable variation from that of combinations of the straight bar form. In fact, the annealing or tempering, which appears to detract from the combined energy of plates or straight bars improves, up to a certain extent, the combination of curved bars; this may probably arise from the circumstance of the proximate position of the opposite poles, by which the deterioration of the similar poles by their near contact is to a certain extent parried, the opposite elements tending to strengthen each other.

101. *Magnetic powers of cast iron.*—The fusion and running of iron into various forms, especially thin bars and plates, by which it is exposed to a greater or less degree of carbonization and a rapid cooling, may be considered favorable to the retention of magnetic energy. It is hence found not ill adapted to the purpose of artificial magnets, although far beneath the powers of properly tempered steel. Cast iron may, in fact, be considered in its magnetic conditions as intermediate between steel

and common soft iron. When cast into hard thin bars or plates it is capable of receiving a high magnetic condition, and it may consequently be advantageously employed for permanent magnets, especially in cases in which economy is an object, the expense of cast-iron plates being extremely small as compared with plates of the best steel. Iron of the very best quality appears to possess the greatest retentive power.

INSTRUMENTS FOR INDICATING THE PRESENCE AND DETERMINING
THE POLARITY OF MAGNETIC FORCES, AND MEASURING THEIR
QUANTITATIVE POWER UNDER VARIOUS CONDITIONS.

102. Instruments for indicating the mere presence of magnetic force, and determining its peculiar polarity, may be termed magnetoscopes; those for its quantitative measurement, under various conditions, may be considered as magnetometers.

Magnetoscopes generally consist of light bars or needles, either suspended by a delicate flexible thread, or attached to an agate or metallic cap, and set on a fine central point. Of these two forms of suspension, the filar suspension is unquestionably the most sensitive. A fine and weakly magnetic steel wire, suspended from a spider's thread of 3 inches in length, would admit of being twisted round 18,000 times, and yet continue to point accurately in the meridian—so little was the thread sensible of torsion.

103. The suspension of magnetic needles, however, by so fragile a thread requires a somewhat dexterous and practiced hand.

An extremely light suspension, not so difficult as the former, consists of a single filament from the thread of the silkworm. For less refined purposes coarser filaments may be employed, and their ends, by a little practice, easily tied into loops. We may also employ occasionally filaments of very fine flax, cotton, and the human hair.

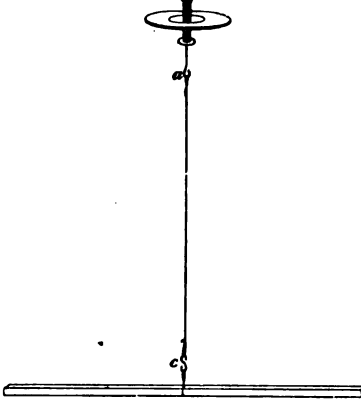
104. In many cases it is desirable to terminate the extremities of the suspension in small open loops; such loops may consist of slight sewing silk, waxed, and secured by paste, or some other cement, to the paper slips, the paper coming between the extremities of the silk; the ends of the silk may be touched with a little common varnish, glue, or gum, and pressed between forceps close to the paper. Loops of thin silver or copper wire, flattened at their ends, may be affixed to the paper in a similar way. These loops admit of further attachment to magnetic bars or needles, and to a point of suspension by intermediate light double hooks of fine wire.

105. A small stirrup, formed by a light plate of copper or silver, has been sometimes attached to the lower extremity of a suspension thread, for the reception and retention of any needle or bar we desire to employ. It is, however, generally more accurate to fix the thread to the center of the needle itself. Light needles or bars are best managed in the

following way: Let a very fine central vertical hole be drilled through the edge of the bar into a hole drilled transversely to the bar, and passing also through the center, the bight of a fine silk loop may then be readily passed up through the central vertical hole, and secured within the bar by a common knot. We may now suspend the bar from the loop of the suspension thread by an intermediate small double hook.

The annexed figure, 67, represents a light bar thus suspended, in

Fig. 67.



which *a c* is the thread of suspension, and *c* the double hook connecting the loops of the thread and bar. Very small double metallic forceps, with compressing rings, or a cleft wire or piece of wood, will be sometimes useful in suspending magnetic bars and needles; in this case the small paper slips terminating the suspension are placed between the forceps. Everything, however, connected with the suspension should be as light and delicate as it is possible. Small suspension hooks are easily turned up from fine copper or silver wire by means of round forceps.

106. The Chinese have a very ingenious method of suspending a

Fig. 68.



magnetic needle, which is at once delicate and effective. A small bent slip of brass, *d c e*, Fig. 68, carrying a light ring at its vertex, *c*, is attached to a small conical cap, *d e*, made of very hard metal; the legs *c d* and *c e* of the brass project a little beneath the cap, and are secured to the cap by fine holes drilled through its sides. The needle *n c s*, to be suspended, and which is seldom more than an inch in length and one-fortieth of an inch in diameter, is secured in the ring *c*, and the whole mounted on a fine point of support.

In this arrangement, notwithstanding that the needle is above the point of suspension, yet the center of gravity of the three parts of the system, viz, *n c s*, *d c e*, and *d e*, falls below that point.

107. *Magnetoscope of simple suspension.*—This consists of a short fine magnetic needle, from one-half inch to 1 inch in length, and from one-thirtieth to one-eightieth of an inch in diameter; it may be made of good piano-forte wire, brought to a spring temper. The north side of it should be colored with a little vermilion. It may be suspended by any of the methods just described, and placed within a common lamp-glass, to shield it from currents of air. If the filar suspension be employed, the filament may be about 4 inches in length, and should be attached to a metallic rod, movable with friction through a stopper of fine cork fitted in the upper end of the glass, so as to admit of being raised or depressed through a given space, as shown in the annexed Fig. 69.

These simple instruments are very applicable to experiments on induction, such as already described, and in which the play of the needle should be sensible and manifest.

Magnetoscope needles of greater length and magnitude should be similarly treated, using larger filaments when requisite. If the exhibition of attractive force, without the interference of polarity, be required, soft iron needles may be substituted for the magnetic needles, as in the cases alluded to.

Wheatstone's method of exhibiting small forces by means of short steel needles standing in an erect position on the pole of a powerful magnet constitutes a very delicate form of magnetoscope, especially available in certain investigations.

The arrangements represented in Figs. 36 and 37 may be considered as magnetoscopes of a peculiar kind, applicable to the combined operations of magnetism and Voltaic electricity.

Fig. 62.



MAGNETOMETERS.

108. The quantitative measurement of magnetic forces may be either direct applications of equivalent weight, or any species of equivalent reactive power, as in the reactive force of torsion; or may consist of indirect determinations of force, through the medium of certain relative effects, as in the amount of deviation of a suspended magnetic needle from its line of direction by the influence of a magnet placed at a given distance from the needle.

Scale-beam magnetometer.—The common scale-beam has been occasionally applied to the measurement of magnetic forces. A small cylinder of iron or a magnet is to be suspended from one arm of the beam, and counterpoised by weights in a scale-pan suspended on the opposite arm. The beam being sustained on any convenient support in the usual way, a second magnet or iron is placed on the table, immediately under this, and the attractive force at any given measured distance is estimated by additional weights placed in the scale pan.

Much care is requisite in effecting this experiment. The beam should not be allowed any very considerable play, but be limited in its motions by two vertical forked stops, one under each arm. If the beam, with a given added weight in the scale-pan, be overset by the attractive force, and rest on the stop, we may either increase the distance of the attracting bodies, or increase the weight, so as just to catch the instant of the balance of the force. Or, supposing a given added weight in the scale-pan, we may continue to approximate a magnet towards the suspended iron or other magnet over a divided scale of distance, and catch the point at which the beam turns.

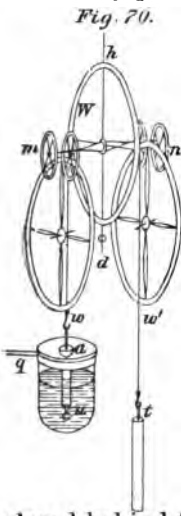
The bent lever, or any self-adjusting balance, may be also employed in a similar way to the measurement of magnetic force.

Of this class of magnetometer the simple contrivance represented in Fig. 28 is perhaps the best adapted to refined investigations, being at

the same time very applicable to the exhibition of elementary magnetic phenomena, especially the phenomena of induction. We have only to find by small weights placed on the suspended cylinder n the value of the degrees of inclination of the beam, and we may refer the force in operation to a fixed standard of weight. The range, however, is limited to the degree of inclination which the beam can support without over-setting.

109. The hydrostatic magnetometer.—This instrument, shown in its general form in Fig. 70, and partially explained in the annexed and following figures, is of such convenient and universal application to the measurement and exhibition of elementary magnetic phenomena and forces, that a particular description of it appears essential.

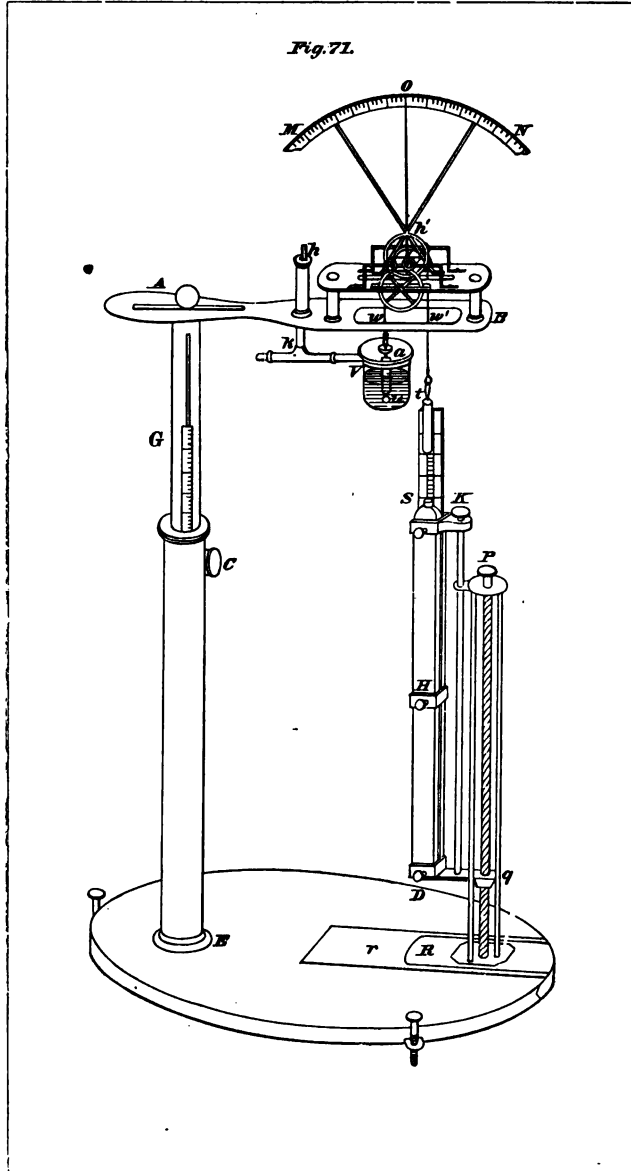
A light grooved wheel, W , Fig. 70, about 2 inches in diameter, being accurately poised on a firm axis, $m n$, is mounted on the smooth circum-



ferences of two similar wheels, $m w, n w'$. The extremities of the axis $m n$ are turned down to fine long pivots, and whilst resting on the friction-wheels $m w, n w'$, pass out at $m n$, between other small check-wheels, two at each extremity of the axis, so that the wheel W cannot fall to either side; great freedom of motion is thus obtained. These friction and check wheels are set on points or pivots in light frames of brass, and the whole is supported on short pillows screwed to a horizontal plate or stage, as shown in $A B$, Fig. 71. The stage is sustained on a vertical column, $A E$, fixed to an elliptical base of mahogany, E , supported on three leveling screws.

There is a short pin, h , Fig. 70, fixed in the circumference of the wheel W , to receive an index of light reed, cut to a point, and movable over a graduated arc, $M N$, placed behind the wheel, as represented in Fig. 71; the weight of this index is balanced by a small globular mass, d , movable on a screw in the opposite point of the circumference; so that the wheel alone with the index would rest in any position, or nearly so. The arc $M N$ is a quadrant divided into 180 parts—90 in the direction $O M$, and 90 in the direction $O N$, the center O being marked zero. Two fine holes are drilled through the wheel, one on each side of the point h , for receiving and securing two silk lines, $w w'$; these lines pass over the circumference on opposite arms of the wheel, and terminate in small hooks, t and w . A cylinder of soft iron, t , or a small magnet, rather less than 2 inches in length and one-fourth inch in diameter, is suspended by a silk loop from one of these lines, w' , and a cylindrical counterpoise of wood, $a u$, weighted at u , and partly immersed in water, is hung in like manner from the other line w . The weights and altitude of the water, and of the vessel q containing it are so adjusted, that when the whole system is in equilibrio, the index $d o$ is at zero of the arc $M N$. With a view

to a perfect adjustment of the index, the water-vessel q is supported in a ring of brass at the extremity of a rod, q , movable in a tube k , Fig 71, this tube is attached to a sliding-piece, $k h$, acted on by a milled head



HARRIS'S HYDROSTATIC MAGNETOMETER.

at h and a screw within the cylinder, which is fixed to the stage $A B$ —so that the water-vessel may be easily raised or depressed by a small quantity, and thus the index be regulated to zero of the arc with the

greatest precision; for it is evident, by the construction of the instrument, that the position of the index will depend on the greater or less immersion of the cylindrical counterpoise au , the weight of which, being once adjusted to a given line of immersion, and a given position of the wheel W and index O , any elevation or depression of the water-vessel q must necessarily move the wheel. The counterpoise au is about $1\frac{1}{2}$ inches in length and full three-tenths of an inch in diameter; a small ball of lead is attached to its lowest part, in order to give it a sufficient immersion, and at the same time balance the iron cylinder t when the float is about half immersed in the water. With a view to a final regulation of the weight, a small hemispherical cup, a , is fixed on the head of the counterpoise for the reception of any further small weights required. This counterpoise is accurately turned out of fine-grained mahogany, and is freed from grease or varnish of any kind, so as to admit of its becoming easily wetted in the water.

The column $A E$, supporting the stage $A B$, consists of two tubes of brass, one, G , movable within the other, $E C$, so that by a rack on the sliding tube G and a pinion on the fixed tube at C , the whole of the parts just described may be raised or lowered through given distances, as shown by a divided scale, G , adjustable to any point by means of a slide and groove in the movable tube G . The brass tubes composing the column are each about a foot in length and an inch in diameter.

110. It will be immediately perceived, from the general construction of this instrument, that if any force cause the cylinder t to descend, then the index $h'o$ will move forward in the direction $O N$, until such a portion of the counterpoise au rise out of the water as is sufficient to furnish, in the fluid it ceases to displace, an equal and contrary force. In like manner, if any force cause the cylinder t to ascend, then we have the reverse of this—the counterpoise obtains an equivalent increased emersion, and the index moves in the opposite direction, $O M$. Thus if we place a weight of 1 grain, for example, on the iron cylinder t , the index will indicate, in the direction $O N$, a given number of degrees equal to a force of 1 grain. If we double this weight, we obtain a force of 2 grains, and so on. The converse of this arises on placing the weights in the cup of the counterpoise au . We may thus reduce the indications to a known standard of weight. It is further evident, that, whether we operate on the system by gravity or by the attractive or repulsive force of a magnet, the indications of force are equally true.

If the instrument be well constructed, and the counterpoise freely wetted in the water, the march of the index in either of the directions $O N$ or $O M$ will correspond to the added weights. Thus, if 1 grain gives 3° , 2 grains will give 6° , and so on. And thus we obtain a continual and known measure of the force we seek to examine, within a given range of degrees of the arc, which will be more or less extensive according to the dimensions of the cylindrical counterpoise, the intensity of the force, and the rate of its increase. When we require to examine

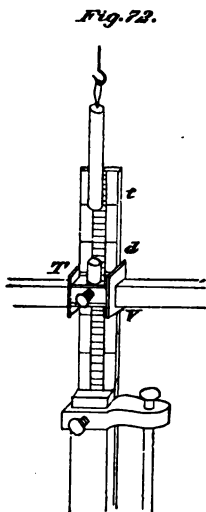
very powerful forces, or forces operating on the suspended iron *t* at small distances, it is requisite to increase the size of the counterpoise float, the indications of which we may always find the value of in grains, as before.

Previously to suspending the cylindrical counterpoise *a u*, the iron cylinder *t* should be placed in equilibrio on the wheel *W* with an equal and opposite weight, as previously determined by an accurate scale-beam, in order to observe if, when loaded with the whole, the wheel *W* and index are indifferent as to position on any part of the arc, or nearly so. The instrument will be sufficiently delicate, if, when loaded in this way with 350 grains, it is set in motion by something more than one-half a grain added to either side.

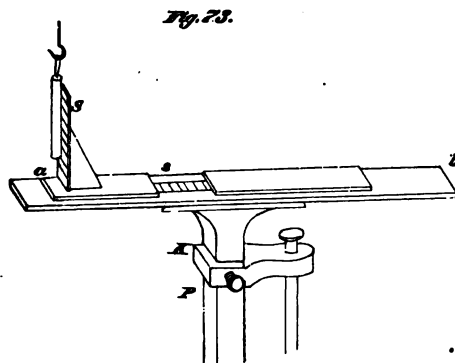
In order to retain the wheel *W*, Figs. 70 and 71, in its position at the time of removing either of the suspended bodies, a small brass prong is inserted at *h* into the arms of the circular segment *M N*, so as to inclose the pin *h* carrying the index: the wheel is thus prevented from falling to either side.

111. The forces requiring to be measured are brought to operate on the suspended cylinder *t* through the medium of induction on soft iron, or by a magnetic bar placed immediately under it, either vertically or horizontally. In the vertical arrangement, shown in Fig. 71, the magnet or iron is fixed against a graduated scale, *S*, by which the distance between the attracting surfaces or bodies is estimated. This scale, together with the magnet *H*, is secured by light bands, *s*, of brass, united by a rod, *D K*. The lower band and rod *D* are both fixed to a stage, *D*, movable between guide-pieces, and acted on through a nut at *q* by a vertical screw, *P q*, about 6 inches in length and three-eighths of an inch in diameter; so that the whole may be raised or depressed, and hence the suspended cylinder and magnet placed at any required distance apart. The regulation of this important element in the operation of magnetic forces is hence provided for in two ways, viz, by the rack at *G* and the milled head at *P*, either of which may be employed, as found most convenient. The scale *S* is of box-wood, 1 foot in length, three-fourths of an inch wide, and one-fourth of an inch thick; it is divided into inches, subdivided into tenths and twentieths of an inch. About 6 inches of the upper part is divided in this way, viz, 3 inches on each side of a central division, which is marked zero; the rest of the piece extends to the stage *D*. The magnetic bar *H* is tied to the scale by compressing screws and simple brass bands, either fixed, as at *D* and *K*, or movable, as at *H*. This adjusting apparatus is secured to a stout brass plate, *R*, fitted by a dovetail into a sliding piece, *v*, forming part of the mahogany stand *E*, so that it may be removed at pleasure. The brass bands and frames at *D H K* are sufficiently capacious to inclose two bars together if required, the superabundant space being filled, when only one magnet is employed, either by a bar of wood or small wedge-pieces in the brass frames.

112. When we require to examine the forces in different points of a moderate-sized magnetic bar, as exemplified in Experiment 10, the bar is laid in a small frame-piece, T V, Fig. 72, temporarily fixed by a compressing screw to the divided scale S, in the way already described, the force on the suspended cylinder t being caused to operate through a small cylinder of soft iron, d , accurately fitted to the surface of the bar; and thus, by sliding the bar along in the holding frame, we may get, approximately, by induction on the iron d , the force of any point in the bar.



When the bar is of considerable magnitude and weight, or we require to examine inductive forces, such as in Experiments 18, 20, 21, the magnets may be placed on a narrow table, $a b$, Fig. 73, supported on a central square pillar, P, fitted to the frame-pieces, K P, of the adjusting apparatus already described, so that the whole may be raised or depressed through any given distance.



In this case the divided scale S, Fig. 73, which measures the distance a between the attracting or repelling surfaces, is a detached piece fixed against one of the perpendicular sides of a right-angled triangle, so as to be anywhere placed upright on the bar; the table ab also has a divided scale, s , movable in a wide groove through its center, by which any distance, s , between magnetic masses may be also shown. When the bars

are very ponderous, two supports are required, one at each end of the table $a b$.

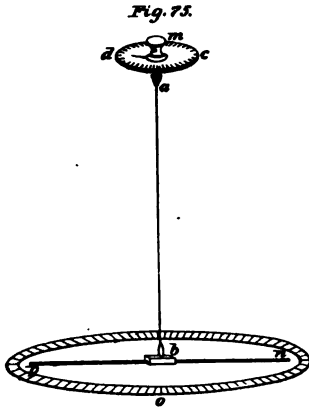
113. Inductive forces are examined vertically by fixing the masses by compressing bands s against the scale S, Fig. 73, as represented in the annexed Fig. 74, and of which we may have, if requisite, two or three in succession.

These arrangements put us in a position to note readily and simultaneously all relative distances and forces under a great variety of magnetic and apparently complicated conditions. In the arrangement, Fig. 74, for example, we may fix a mass of iron, S, at successive distances, S, N, from a magnet, H, and yet preserve the distance, $a b$, at which the induced force operates constant, either by the rack and pinion C, or the milled head and screw P R, Fig. 71, and thus arrive at a measure of the inductive force on the intermediate mass S.

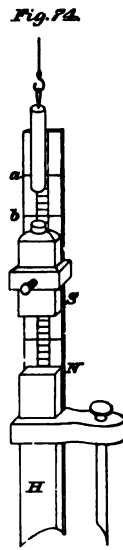
114. *Torsion balance.*—This species of magnetometer is derived from

the reactive or untwisting force of a fine wire when subjected to a certain amount of torsion.

In this instrument, the directive or other force acting on a magnetic bar or needle, $p n$, Fig. 75, is balanced against the twisted force of a fine wire, $a b$, suspended from a point of support, a , and to which the needle or bar is attached, the point of support being the terminating extremity of a vertical wire or rod, $m a$, passing through a collar, a ,



a plate, $d m c a$, and surmounted by a milled head, m . It is here evident that by turning the milled head m , we necessarily turn round the wire $a b$; and if the bar or needle $p n$ resist this twist, we may place the resisting force in equilibrio with the reactive force of the torsion; or if, on the contrary, we apply a force to either pole of the needle $p n$, considered as a lever, then the wire $a b$, resisting the movement of the needle



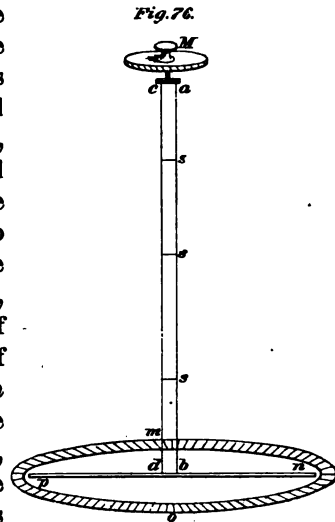
by the torsion impressed upon it, furnishes a balance to the force in a similar way. The amount of twist given to the wire is indicated in degrees, either by a graduated circle, $p b n o$, within which the bar or needle turns, or by a graduated plate $c m d a$, with an index, c , showing by how many degrees the point a has been turned round, and consequently the twist impressed on the wire $a b$. Thus Coulomb found, for example, that with a fine wire about 30 inches in length it was requisite to turn the index c through 35° , in order to force a magnetic needle, $p n$, 24 inches long and about one-tenth of an inch in diameter, through one degree of the circle $p b n o$, that is, to deviate 1° from its line of direction; and thus a comparative value of the directive power at 1° was obtained.

In this instrument the needle $p n$ is fixed in a small stirrup, b , and is inclosed in a glass case, the plate $c d$ and wire $a b$ being supported in a tube of 30 inches in length, raised from the center of the framework of the case.

Coulomb has shown that the reactive force of the wire $a b$, when subjected to a moderate twist, is directly proportionate to the angle or arc through which the extremity p of the needle has moved, and is not affected by the weight of the suspended body.

115. *The bifilar balance.*—In this magnetometer a reactive force is derived from the gravity of a needle, $p n$, Fig. 76, or other body, suspended centrally by two parallel threads, $a b, c d$, from a short cross-wire, $c a$, and which can be moved round so as to cause the threads to turn as it were upon each other, by which the mass of the needle $p n$, if resisting the twist, is insensibly raised, and its gravity or weight thus made to balance any given force operating on it; or, supposing the needle

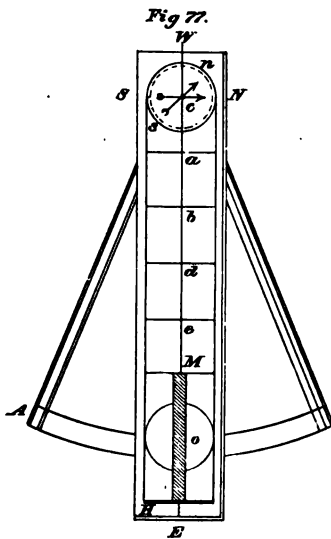
$p n$ to be at rest on the magnetic meridian, when the two threads of suspension are vertical and parallel, and it be caused to deviate from this position by the operation of a repulsive force on one of its poles, p , then the two threads, $a b, c d$, will become more or less oblique to each other, and the needle will be raised by a small quantity, and the tendency of the needle to descend by gravity will be in equilibrio with the force acting on the poles of the needle, considered as a lever. Similarly, by turning the cross-wire $c a$ by means of the micrometer M through any number of degrees, we tend to turn the needle $p n$ from its line of direction, and so twist the threads upon each other in a similar way, the directive force of the needle may be thus estimated. The other arrangements are similar to Fig. 75.



The reactive force in these bifilar suspensions is directly as the distance between the threads and inversely as their lengths. It is also directly proportionate to the weight of the needle or other suspended mass, and is as the sine of the angle of deflection of the needle.

To prevent the threads from collapsing upon each other, small stays, $s s s$, of light cork or reed are inserted at given distances between the threads.

116. Magnetometer of declination.—This instrument consists of a light



short needle, Fig. 77, delicately suspended within a graduated ring of card or metal, $s s n N$. The needle and divided circle are fixed in the axis, and near one extremity of a straight mahogany board, $E W$, movable about a point, c , concentric with the center of the needle, so that it may be readily turned for a short distance to either side of an arc, $A B$, forming a base of support.

A central or axial line, $W E$, is drawn on the board, and another line, $S N$, at right angles to this, passing through the center c . Other lines, $a b d$, &c., are drawn on the board parallel to $S N$, denoting the distance in inches of the points $a b d$ from the center of the needle.

The whole apparatus is so placed as to make the needle c coincident with the line $S N$, which may be finally and completely effected in turning the board $E W$ a little to the right or the

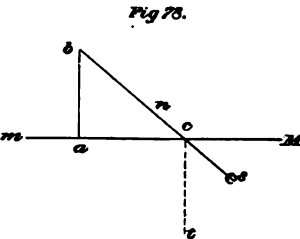
left upon the center c . This adjustment complete, the axial line $E W$ will be in an east and west direction, being at right angles to the meridional direction $S N$ of the needle.

The force of a magnetic body, M , is estimated by placing it at a given distance, $M c$, from the center of the needle, immediately in the axial or east and west line of the board $E W$, and at right angles to the direction $S N$ of the needle, and noting the angle of deviation of the needle in degrees of the graduated circle $s S, n N$. If the force of a magnet, M , for example, be examined in this way at a distance, $M c$, from the center of the needle, of five or six times the length of the needle, then the tangents of the angles of deviation of the needle, as found in the ordinary mathematical tables, afford a very fair approximative measure of the force or power of the bar. Thus, if the angles of deviation caused by two magnetic bars, whose separate powers we wished to determine, were at the same distance, $M c$, 12° and 40° , respectively, then the relative forces, as found in the column of tangents for these angles, would be as 2125 to 8390, or as 1 : 4, very nearly.

If the needle c were indefinitely short in respect of the magnet M , or the distance $M c$ indefinitely great, then the force operating on the needle would be exactly measured by the tangent of the angle of deviation; but since we cannot employ a needle indefinitely small, or distances indefinitely great, we cannot realize in practice an absolutely perfect result. The errors, however, diminish rapidly with the distance; in fact, the force is not really exerted in the direction $M c$, but more or less obliquely on either side upon the arms of the needle. The power also of the magnet is not the same in the deviated position $s n$ of the needle as in the rectangular position $S N$; hence, if we examine the force at small distances from the needle, certain corrections will be requisite, tending to complicate the experiment, but which diminish rapidly as the distance is increased.*

For the purpose of convenience and accurate observation, the magnetic bodies whose forces we require to examine are placed on a circular plate, O , movable about a center, O , on a short rectangular board, $H M$, beneath. This last board moves between guide-pieces on the board $E W$, so as to admit of the magnetic body M being set at any required distance from the needle $S N$, whilst by the revolving circular plate O

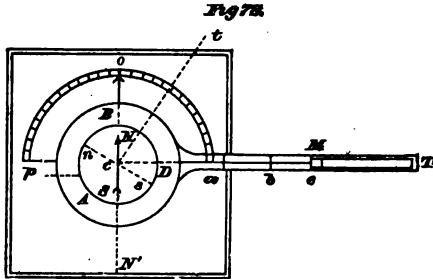
* Let $n c s$ in the annexed Fig. 78 represent a magnetic needle deviating from the magnetic meridian $M c a$ by a force acting in direction $t c$, as in Fig. 77. Take $c a$ to represent the horizontal or directive force of $n s$; draw $a b$ perpendicular to $M m$, meeting $s n$ prolonged in b ; then we have $a b$ as representing the deflective force operating in direction $t c$ as before. But in this triangle $c a b$ we have, by trigonometry, $c a : a b :: \text{rad.} : \text{tangent of } a c b$. If horizontal force $c a$ be called unity, or 1, we have $a b \times R = \text{tangent of the deviation } a c b \times 1$ or deflective force = tangent of deviation, R being also considered as unity.



we are enabled to reverse the position of a magnet, *M*, without deranging its position, and so examine the force of the opposite pole.

The precise situations and directions being once obtained, the respective movable parts are fixed by appropriate screws and clamps.

117. *Magnetometer of deflection.*—This instrument, represented in the



annexed Fig. 79, is very similar to the former in principle; the difference being in the position of the magnetic body under examination, which is always placed at right angles to the direction of the deflected needle. In this figure, *SN* is a delicately suspended needle, with an accurately divided

circle or card, *c*, by which its angular deflections from the magnetic meridian are shown. The needle and card are supported on a fixed point or center, *c*, so as to be a little raised above a circular disk of mahogany, *A B D*, concentric with this needle, and which is movable about the central point *c*, immediately under it.

The circular disk *A B D* carries a long projecting arm, *D T*, in the direction of a diameter of the circle; an axial line, *D T*, is drawn upon this arm, which, if continued, would pass through the center *c*, immediately under the center of the needle. This line is divided, as in the former case, Fig. 77, by other transverse lines *a b e*, showing the distance of these points from the center *c*. The whole is placed on a firm mahogany base or clamped board, furnished with a divided semicircular arc, *p o a*, concentric with the graduated circle of the needle. This arc is divided on each side of the center *o*, up to 90° , the point *o* being the zero of the arc. By means of a light index, *B o*, attached to the movable circle *A B D*, we are enabled to estimate, on a large scale, the angular quantity through which the circle has been turned either way.

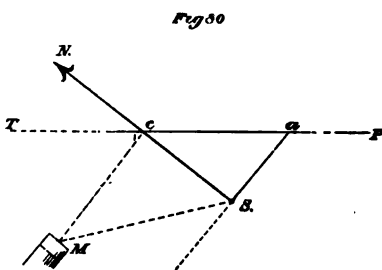
The instrument being adjusted so as to bring the line *D T* perpendicular to the direction of the needle or magnetic meridian *N o* and the index *B o*, at zero of the arc *p o a*, then the force of any magnetic body *M T* is measured, in placing it in the line *D T*, at a given distance, *C M*, from the center of the needle *S N*; in this case the needle will stand more or less oblique to the line of the deflecting body *M*, and will assume some other direction, *s n*. We now proceed to turn the circular board, *A B D*, and arm, *D T*, in either direction, until we again bring the line of deflection at right angles to the new direction of the needle. Thus, when the new direction becomes *s n*, the line of deflection should be in the direction *t c*. Now, the angular quantity by which the arm *D T* has been turned, in order to establish the equilibrium in this precise position, corresponds to the angular deflection of the needle, that is, to the angle *n c N*, and this angle therefore becomes measured on a large scale, *a o p*, by the index *B o*, however small a needle, *S N*, we may find it convenient to employ. Now, the force of the deflecting body *M T*, if

the distance $c M$ be many times the length of the needle, will be very nearly as the sine of the angle of deflection as given in the ordinary mathematical tables.

Thus, if two magnets placed at the same distance $c M$ from the center c , or the same magnet placed at different distances, cause deflections of 20° and 43° , respectively, then the relative forces will be as 3420 and 6819, or as 1 : 2, very nearly.

118. In experiments of this kind the needle $N S$ may be considered as a pendulum, which, when drawn aside from its natural position, tends to return to it; and if by any equivalent statical force acting in a given direction we maintain the pendulum in any other position at any given angle to its natural position, the amount of such statical force, as is proved by mechanics, will vary with the sine of the angle of deviation. The conditions, however, of a magnetic needle, considered in this way, and sustained at a given angle to its meridian by a deflecting magnetic force, are both in this and the preceding case, Fig. 77, extremely complicated and troublesome. The force which we measure is actually the resultant of all the forces of the magnet, and we have necessarily to consider it as proceeding from four elementary actions, two attractions and two repulsions; that is to say, the repulsions of the similar and the attractions of the dissimilar polarities (14). We must hence endeavor to place the experiment under such practical conditions as will enable us to consider the result as derived from a central force operating upon the poles of the needle in a given direction. In Fig. 79 we have supposed the force to be directed from one pole of the deflecting magnet M , in a direction always perpendicular to its actual position; still, in this, as in the former instance, Fig. 77, the forces are not really so exerted; they fall more or less obliquely to the needle upon each side of the center, and it is only when the needle is supposed indefinitely short, or the distance $C M$, Fig. 79, indefinitely great, that we can really consider these oblique forces as perpendicular to the line of the needle. We may, however, so consider them for most practical purposes, when we make the distance $C M$ exceed five times the length of the needle, whilst the opposite pole T of the bar, being still farther removed, the forces from this pole may be so far neglected. In this way we may arrive at very fair and valuable approximate measures.*

* Let $S N$, Fig. 80, be a magnetic needle, of which the line $T P$ is the natural direction or meridian, and let M be a magnet causing the needle $S N$ to deviate from its meridian by some given angle, $P C N$, and holding it there by a force supposed to be collected in the pole M , and to operate in the direction $M c$, or at right angles to the actual position $S N$, of the needle, and upon a center of force, N or S , resident in the poles of the needle. Then, taking $a c$ to represent the force urging



For the better convenience and accuracy of observation, the magnet (M, Fig. 79) may be placed on a movable circular board and slide, as in Fig. 77, so as to turn the poles into an opposite position and adjust the distances without disturbing the bar.

119. This last magnetometer, as is evident, is convertible into the former by simply observing the deviation of the needle S N when the arm D T is at right angles to the magnetic meridian; and conversely the magnetometer, (Fig. 77) may be employed as a magnetometer of rectangular deflection, by turning the board E W, together with the needle and magnet, into such a position as will bring the needle again at right angles to the axial line of the board. If we then remove the magnet M, the needle returns to its meridian, and we are enabled to observe the number of degrees by which it has been deflected. The great advantage of the latter arrangement, Fig. 79, is that we are enabled to employ a very short needle, and yet observe the degree of deflection on a very large circular arc, *a o p*. This, however, might still be effected in Fig. 77, by applying an index and large graduated arc to measure the angular movement of the extremity W of the board E W, about the center *c*. In this case the angular quantity requisite to turn the axial line E W, in order to place the needle at right angles to that line, would represent accurately the deflection of the needle from its meridian.

120. *Magnetometer of oscillation.*—This magnetical instrument consists of a light magnetic bar, or needle, N S, Fig. 81, suspended by a fine silk filament, *a i*, from a fixed point, *i*, within a graduated circular ring, *a S b N*. The card and needle are mounted in a light wooden frame, *t u t'*, carrying an elevated and narrow cap and nut, *c*, for the thread of suspension. The whole is placed on a slightly elevated table, *t t'*, indicated in the figure, and so as to be movable about a central pivot, A, which, if prolonged, would pass through the center of the needle and card N a S b. The thread of suspension is attached to the extremity of a rod, *c a*, which is acted on by a milled head and screw at *c*, so as to elevate or depress the bar S N by any small quantity;

the needle in its natural meridian, T P and *a S*, perpendicular to S N, the force by which the needle is sustained at a given angle, *a c S*, we have from trigonometry—

$$c a : a S :: \text{sine of } a S c : \text{sine of } a c S,$$

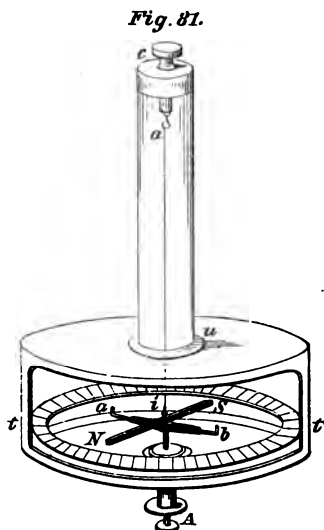
and thus deduce

$$a S = \frac{c a \times \sin a c S}{\sin a S c}$$

But if, as in the case of the instrument (Fig. 79), the distance M c be taken so great as to admit of the obliquity of the action in direction M S being neglected, and *a S* to be parallel to M c, or nearly so, and that this direction is always perpendicular to the needle, so that angle *a S c* becomes a constant—being a right angle or unity—and if, moreover, we only consider the comparative deflecting force without regard to the horizontal force *c a* urging the needle to its natural meridian, then we may neglect sine of *a S c* and force *c a*, and we have for the above equation—deflecting force *a S* = sine of *a c S*.

and adjusted to the plane of the graduated ring $a S b N$ there is a forked lever, $a b$, carried by a rod, $A i$, passing through the base of the frame, by which, in turning the milled head at A , the needle or bar may be seized, as it were, equally on each side of the center, and turned to any given points of the graduated circle.

The opposite points $t t'$ of the card are marked zero, and the card is graduated up to 90° on each side of these points. The axis of the bar $S N$ is brought to coincide with these points by turning the frame carrying the card about the center o . Two indexes, $N S$, of fine platinum wire are inserted in thin vertical slits cut on the extremities of the bar, and there are two sights in the frame at $t t'$, by which the position of the opposite points of the card and needle may be accurately placed in the line of the magnetic meridian. This instrument being thus adjusted, the bar $S N$ is turned aside by the forked lever $a b$ to any given angular quantity shown on the card. The lever is then quickly turned back, and the bar allowed to vibrate for any given period. The times and arcs of vibration are carefully noted, and from this the force urging the bar is deduced.



The frame $t u t'$ may be covered with a thin glass shade, to screen off currents of air from the vibrating needle, having an open end at u for the passage of the vertical narrow frame $c u$.

121. The principle of this magnetometer is based on the fact that a vibrating magnetic needle may be considered as a species of pendulums and the condition of the needle with regard to the magnetic directive force operating on it is very similar to that of a lever movable on a horizontal axis, and acted on by any other force, such as gravity—such, for example, as the case of the compound pendulum—so that the same laws apply to both these cases. Now, it is proved by the laws of oscillating bodies—

(1). That the time in which the same pendulum oscillates under different degrees of power will be inversely proportional to the square root of that power.

(2). That the force operating on the pendulum will be in the inverse ratio of the square of the time.

(3). That the time being the same, the force will be directly as the square of the number of vibrations.

Such are the general laws requisite to be kept in view for our present purpose. In the adaptation of the magnetic pendulum to the measurement of magnetic forces there are certain other considerations to be

taken into the account, in the application of a vibrating bar or needle to particular and refined inquiries in magnetism, which will be noticed hereafter.

122. As a practical illustration of the application of the magnetometer of oscillation, Fig. 81, to the measurement of magnetic forces, suppose the bar S N, under two different states of intensity, as produced by the methods of single and double touch, already described, had been found to make within given small arcs of vibration

First 10 vibrations in 80 seconds (a);

Second 10 vibrations in 40 seconds (b);

then, by the laws just given, the force, or magnetic power of the bar, would in the second case (b) be four times as great as in the first (a).*

123. The rate of vibration of magnetic bars as a measure of force may be occasionally observed by a simple suspension from a fixed point. Coulomb deduced in this way the force of the bars constituting his large compound magnet, as produced by various methods of magnetizing.



Fig. 82

124. A very simple and ready form of the magnetometer of oscillation, especially in such investigations as require a short and fine vibrating needle, consists in the suspension of a small piece of magnetized steel wire within a common lamp-glass, closed at the top by a cork, through which the wire of suspension may be easily moved. A graduated ring of card-board should be made so as to encircle the glass at the position of the needle, and the whole may rest on a circular grooved piece of mahogany. This instrument is represented in Fig. 82. The needle suspended within this glass may be put into a state of vibration by the external influence of a small piece of iron, or a weak magnet.

125. *The dipping needle.*—We have already seen that the natural position of the magnetic needle, when free to move into any position, is not always horizontal, but is a combination of a horizontal and vertical direction, so that the needle commonly endeavors to place itself in the plane of the magnetic meridian, in a direction more or less inclined to

* Let the force urging the bar in the first case (a) be called f ; in the second case (b) be called f' .

We have then by law

$$(1) \quad 80^2 : 40^2 = \sqrt{f} : \sqrt{f'} = 2 : 1$$

that is,

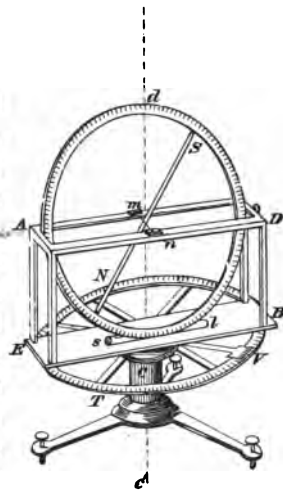
$$\sqrt{f'} = 2\sqrt{f}$$

If we call f unity or 1, then $\sqrt{f'} = 2$ and $f' = 4$; hence force f' is four times as great as force f . We have next by law (2) $f : f' :: 40^2 : 80^2 :: 1^2 : 2^2$, or as 1 : 4, which is the same result. By law (3), we have, in taking the number of vibrations performed in the same time, say for the first case (a), reduced to 40 seconds, $f : f' :: 5^2 : 10^2$, that is :: 25 : 100, or as 1 : 4, as in the other cases.

the horizon. The magnetical instrument by which the amount of this inclination is determined has been termed the *dipping needle*, and is represented in Fig. 83.

N S represents a light magnetic bar or needle of a long lozenge form, about 10 inches in length, which, previously to being rendered magnetic, is set on a short axis, $m n$, and is very accurately poised about its center of gravity, through which the axis is passed, so as to be quite indifferent as to position. The axis $m n$ is turned down at its extremities to very fine cylindrical pivots; these rest on two finely-polished agate planes, $m n$, supported on two cross-bars, A D, of a light rectangular frame, A D B E. The platform or cross piece E B of this frame is solid, and fixed to a circular plate beneath, accurately ground to a similar plate fixed on a vertical pillar, C, so that by means of a vertical axis, which plays in a socket in the pillar C, the whole may be turned evenly and centrally round into any azimuth. The cross piece E B, which has a level, S l, fixed in it, gives support to a finely divided circle, A d l, in the plane of which the bar N S moves; the axis $m n$ is so placed as to pass accurately through the center of this circle. The whole is mounted on the central pillar C, and can, as just observed, be turned into any required azimuth about a supposed vertical axis, $c d$, passing through the center of the needle. The precise angular quantity through which the needle is turned is measured by a *vernier*, V, attached to the under part of the platform E B, and a graduated azimuth circle, T N V, fixed to the central pillar of support; the whole is placed on a light, firm base, furnished with three leveling screws, for the requisite leveling of the instrument. The vertical circle A d l is divided upon silver to 10' of arc. The agate pieces $m n$ are adjustable to the same horizontal plane by screws bearing upon their lower edges, and there is a light interior frame acted on by a lever at D, furnished with Y-pieces at $m n$, and movable on an axis at one extremity, A, by which the axis of the needle S N may be lifted off the agate planes $m n$, and be again let down on them, without disturbing its final position. The whole is covered by a light case of wood and glass resting on the platform piece E B, but not represented in the figure, so as to shield the needle from the air, and there are also two movable arms attached to a horizontal bar connected with the case, which carry lenses for reading off the degrees of the divided circle S.

Fig. 83.



The instrument here described is after the construction of M. Gambey, of Paris.

126. In order to determine by this instrument the dip or inclination of the magnetic needle in any given spot, we place the instrument on a

steady base, free from the presence of iron, and having accurately leveled it, proceed to adjust the graduated circle $A d l$ in the magnetic meridian. This is effected either by removing the needle of inclination $S N$, and placing a balanced horizontal needle, made expressly for the purpose, within the frame $A m D n$, or in any other situation adapted to it, or by turning the instrument so as to bring the dipping needle into a vertical position. It will be then at right angles to the magnetic meridian; and we have then only to turn it 90° from this point, as shown on the azimuth circle $T N V$. Having determined the direction or the magnetic meridian, the plane of the circle $A d l$ is finally secured in that direction by a small clamp-screw at C . We now remove the horizontal needle, if that be employed, and replace the needle of inclination $S N$, allowing it to vibrate freely. When it is at rest, we turn the milled head lever at D , and lift the axis $m n$ gently off the agate planes by means of the y -pieces; when again let down it will be accurately in the center, and in the plane of the divided circle. Supposing we had an absolutely perfect instrument, the needle would now mark the precise angle of inclination at the place of observation; but there are mechanical errors, as just observed, quite inseparable from the construction of the instrument, which we can only hope to compensate by a mean of experiments. We therefore first take a few successive observations, and note the angle at which the needle rests after putting it into vibration. This should be repeated with the axis $m n$ reversed in position on the agates. We then turn the face of the instrument 180° , as shown by the circle $T N V$, that is completely round, and make a similar number of observations. We now remove the needle $S N$, and by the processes of magnetizing before given to reverse its poles, and take a similar series of observations; so that we have then to take the mean of a given number of observations—say 10.

First, with the face of the instrument, suppose to the east.

Second, with the face of the instrument, suppose to the west.

Third, with inverted poles, face to the east.

Fourth, with inverted poles, face to the west.

The nearer these observations accord, the more perfect is the instrument; but they will certainly differ by some small quantity. If we add the whole together, however, and divide by the number of observations, the resulting quotient will be very near the true inclination of the needle.

127. It being almost impossible to construct an absolutely perfect instrument for determining the inclination of the magnetic needle at once and by a direct experiment, other indirect methods have been proposed, by which the errors inseparable from the difficulty of construction are sought to be avoided. One of these consists in observing the angular deviation of the needle from the vertical position taken in a series of planes at right angles to each other, by turning the instrument round on its vertical axis. If we take the squares of the tangents of the observed angles of deflection from the vertical in each pair of planes, and

deduce a mean from these results, we obtain the square of the tangent of an angle, which, if added to the true angle of inclination, would complete a right angle or 90° , hence called the *complement of the dip*; from this it is evident that the true angle of inclination can readily be found by the ordinary mathematical tables.*

128. Another method of observation consists in observing the time of a given number of vibrations of the needle in the plane of the meridian, and in a plane east and west, or at right angles to this; that is to say, in the inclined and vertical positions of the needle. We then divide the square of the times, say of 100 vibrations in the plane of the meridian, by the square of the time of the same number when the needle is vertical in an east-and-west plane; the quotient is the sine of the true angle of inclination, from which the angle itself is easily found.

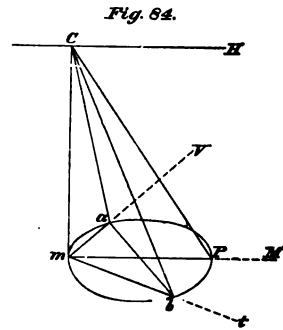
This method principally applies to places in which the dip is not very considerable. When the inclination is considerable the following method has been resorted to: first observe the time of a given number of vibrations in the plane of the meridian, as before; then suspend the needle by a silk fiber, branching and extending below a little on each side the center, so as to produce a perfectly horizontal position. Let the needle now vibrate freely in a horizontal plane. Divide the square of the time of a given number of vibrations in the inclined position by the square of the time of the same number in the horizontal position, and we then have the cosine of the true inclination or dip, from which the angle itself is easily found by the ordinary tables.†

* In the annexed Fig. 84, let C be the center or axis of the needle, CP the true position of inclination from the horizontal line CH in the plane of the magnetic meridian m M. Then in turning round the instrument, it is found that when the face is at C m, or at right angles to the meridian m M, the needle will be in a vertical position, C m, and will, in turning take all intermediate positions, describing a cone m C P b m a. Let m C a and m C b be the angles of deviation from C M, as observed in two planes, m V, m t, at right angles to each other. Then in right-angled triangle, a m b, we have

$$(m a)^2 + (m b)^2 = (a b)^2 = (m P)^2$$

since a b and m P are diameters of the same circle, m a P b; but by trigonometry, m a and m b are the tangents of the observed angles, m C a and m C b; we may hence obtain from the squares of these tangents the square of m P, which is in like manner the tangent of the angle m C P; that is to say, of the complement of the angle P C H, or true inclination below the horizontal line C H. From this the angle of inclination, P C H, or true dip, may, as is evident, be deduced by the ordinary trigonometrical tables.

† These processes are founded on the resolution of the force causing the needle to vibrate. When oscillating in its natural or inclined position, it oscillates by the action of the whole *directive power*; but when oscillating in a vertical or horizontal position, only a portion of the whole directive power comes into play. Completing the trigonometrical construction of the forces according to the method given, Fig. 78, the force in the vertical position becomes finally represented by the sine of the angle of incli-



As it is of importance in this experiment to obtain a true horizontal direction, we cannot be too careful in completing the position of suspension. The following is a simple and ready method of observing whether the needle be suspended horizontally. Fill an open vessel of any kind with water, which should be tinted with a little common blue; hold the needle by the suspension thread over the water, so as to observe the reflected image of the needle: if the two lines of the needle and its image be parallel, then it is evident, from the nature of the experiment, that the needle is perfectly horizontal; if not, we must adjust the branch of suspension until this result be obtained.*

129. *Mayer's dipping needle.*—With a view of avoiding the errors incidental to the dipping needle as usually constructed, Mayer employed a needle having a projecting steel screw, very accurately centered, on which a small bass ball was made to traverse, so as to deflect the needle from the true inclination by any given quantity. In this case, as is evident, we never get the correct dip in any one observation, the position of the needle being partly due to gravity; by reversing the instrument, however, as in the preceding experiments, the effect of gravity becomes separated from the magnetic force, and thus the true dip is ascertained.

130. All these indirect methods of observation, although extremely worthy of consideration, are still open to many sources of error inseparable from such investigations.

Sabine, in 1821, determined the inclination of the needle in London, by the two methods of oscillation, and by Mayer's needle, and arrived at the three following results:

Mayer's needle, $70^{\circ} 2'.9$. Methods of oscillation, $70^{\circ} 4'$ and $70^{\circ} 2'.6$.

Barlow, a few years subsequently, by Gilbert's dipping needle, obtained the following:

$69^{\circ} 58'.4$. $70^{\circ} 0'$. $69^{\circ} 53'$. $70^{\circ} 1'.8$.

nation, and in the horizontal position by the cosine—calling the whole, or total force, unity or 1. Let, therefore, d express the dip or angle of inclination, t and T the times of a given number of oscillations in the inclined and vertical positions of the dipping needle; then, as the forces are inversely proportional to the squares of the times of vibration, we have—

$$1 : \sin. d :: T^2 : t^2;$$

that is to say,

$$\sin. d = \frac{t^2}{T^2}$$

Taking the oscillations in the inclined and horizontal positions, we have, in substituting $\cos. d$ for $\sin. d$,

$$\cos. d = \frac{t^2}{T^2}$$

* This method of obtaining a horizontal line was first proposed in 1832. It is extremely simple and perfect, and has been since practiced in observatories. The error of horizontality by reflection being double the real error, it is very easy to detect the least deviation from the horizontal position.

By the latter observations with Gilbert's needle, there appears to be an uncertainty or difference in the action of the needle, of about $9'$, which, considering the nature of the force acting on it, is inconsiderable. If we suppose the needle within $9'$ of its true position, then the force acting on it, being as the sine of the inclination, will be to the force acting on it at 90° , or at right angles from its true position as radius to the sine of $9'$, or as $1 : .0026$. Now this is so small a result, that the least defect in the balancing, or in the axis of motion, or any minute roughness in the agate planes, or the interposition of dust, or other accidental causes of disturbance, would be sufficient to arrest the needle in such a position.

131. The axis of the dipping needle by Michell, made by Nairne, for the Board of Longitude, in 1772, rested on friction wheels, four inches in diameter; the extremities of the axis being of gold, alloyed with copper, and turned down to fine pivots. The needle in this instrument was a foot in length. The principle of agate planes was adopted by Cavendish, in the dipping needle made for the Royal Society, in 1776.

132. *Dipping needle deflector.*—We must not close this branch of our subject without noticing a most valuable and ingenious instrument, by Mr. R. W. Fox, of Falmouth, and termed by him a *dipping needle deflector*. In this instrument the needle, being accurately poised, is mounted on an axis, and placed within a cylindrical case, faced with glass, similar to a watch-case. The needle is about seven inches in length, the pivots of the axis turn in jewels, and there is a finely divided circle, with a vernier, for estimating the inclination of the needle. The whole is set vertically on a firm tripod base, with leveling screws, and admits of being turned into any azimuth. A small telescope, movable in a vertical plane, and furnished with cross wires, is attached to the back of the case, to which is added a brass tube with a lens, for throwing a bright spot of light upon a white plate behind it. For solar observations there are two small tubes of brass, which may be applied to the telescope tube, for receiving two cylindrical magnets, and which are so arranged as to admit of being turned into certain positions for deflecting the needle. The back of the case has also a divided circle on it, with a vernier carried by an arm at right angles to the telescope.

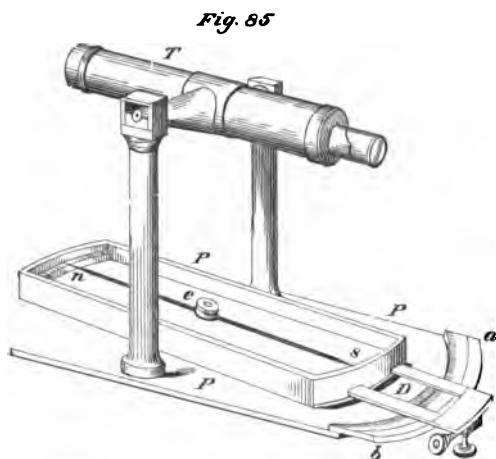
In measuring the angle of the dip by this instrument, we carry out a series of common observations, in the way already described. The observed dip is to be corrected by screwing on one of the deflectors at right angles to the telescope tube, so as to deflect that end of the needle nearest to it. The deflector is now turned a given number of degrees from the observed dip, so as to deflect the needle by a certain amount, and then a similar number of degrees in the reverse way, so as to deflect the needle in the opposite direction; then, supposing the needle, in these two cases, to stand first at 52° , and secondly, at $87^\circ 10'$, the mean of these would be $69^\circ 35'$, the angular quantity sought.

INSTRUMENTS FOR DETERMINING THE DECLINATION, AND FOR MEASURING CERTAIN SMALL PERIODICAL CHANGES IN THE HORIZONTAL AND INCLINED NEEDLES.

133. The declination and inclination of the magnetic needle not being, as just observed, everywhere the same, and being, further, found liable to certain small fluctuations of a secular character, it becomes a matter of great scientific importance to ascertain the amount and nature of such changes; and with this view certain instruments have been invented, which remain now to be briefly described.

134. *The variation compass.*—A sample of this class of instrument is that employed by the late Colonel Beaufoy for the capital series of observations recorded by him in the "Annals of Philosophy," be-

tween the years 1813 and 1821. It is partially represented in Fig. 85.



In this compass the needle *s n* is a slender and pointed cylinder, 10 inches long, and only the one five hundredth of an inch in diameter. This needle is placed within a narrow cylindrical case or box, *s C n*, the base of which is a brass plate movable upon a central pin, *C*, under the point of suspension of the needle. This plate has two segments

of a circle, one under the needle at each extremity, upon which is drawn a central or axial line, and at the extremity *D* of the box is a vernier and index, pointing to the divisions of a finely divided arc, *a b*, attached to a large plate of brass, *P P*, beneath it, and movable also on the central pin at *C*. The plate *C D*, carrying the vernier, has a frame furnished with a clamp screw and a tangent screw, one to fix it to the arc *a b*, the other to give it a slow motion about the center *C*. The lower plate *P P* sustains a transit telescope *T* immediately over the center of the needle. The whole is placed on a firm mahogany base not shown in the figure; this rests on three leveling screws, and there is also a microscope placed over one extremity, *s*, of the needle, by which its coincidence with the axial line on the segment beneath is minutely observed. The object being to convey a simple idea of the principle of this instrument, several minor details have been omitted both in the figure and the description, for the sake of perspicuity.

In order to observe from time to time the smallest variation in the direction of the needle with this instrument, it is first accurately leveled, and the vernier *D* set at zero of the arc. The telescope *T*, with an ad-

ditional object-glass, is then directed to the axial marks under the extremities *s n* of the needle, by which we ascertain them to be in the plane of the motion of the telescope; if not, the telescope must be rectified so that they shall be. We now adjust the telescope in the true meridian by the usual transit of the stars across it; an adjusting screw acting on the brass plate *P P*, carrying the telescope and fixed to the base beneath, but not shown in the figure, being used to turn the whole about the center *C* when requisite. If the instrument is to be a fixture, distant marks are set up to fix the direction of the meridian line. We now allow the needle to settle quietly, and then turn the box *s C n* until the needle corresponds with the axial line or the segments beneath; the clamp screw, in the frame at *D*, is then fixed, and we proceed to give the compass box a slow motion by means of the side or tangent screw, until an exact coincidence, as seen through the microscope, is obtained; the vernier at *D* now shows the precise variation of the line of the needle from the true meridian.

135. Barlow's Variation Needle.—The small amount of variation in the direction of the magnetic needle observable by such instruments as the variation compass may be considerably magnified by a most ingenious process proposed in the year 1823, by Professor Barlow, of Woolwich. It occurred to this distinguished philosopher, that if a delicately suspended needle were placed under the influence of magnetic bars, so as to deflect it from the meridian, even so as to render it indifferent as to directive position, then the changes in the directive force operating on it, whatever it be, would become extremely sensible, and distinctly marked by changes in the position of the needle. Suppose, for example, by the application of a magnetic bar, as represented in Figs. 77, 79, the needle were deflected so as to stand 8 points from its natural direction, it would then be observed to vary through more than 3° in the course of 24 hours.

In this kind of experiment the needle of observation may be brought, by means of magnets properly disposed, into any required position. We may, for example, deflect it eastward or westward of its meridian, or even reverse its position altogether. We shall have occasion to refer to the results of this method of observation hereafter.

136. The declination magnet.—This instrument consists of a delicately suspended magnetic bar *N S*. Fig. 86, about 2 feet in length, $1\frac{1}{2}$ inches wide, and $\frac{1}{4}$ of an inch thick. This bar is furnished with two sliders of brass, *a b*, one of which, *a*, carries a lens, the other, *b*, a compound plane glass, consisting of two plane glasses brought close together, and having between them a cross of cobwebs adjusted to the focus of the lens. The suspension thread consists of several fibers of unspun silk, and deprived of all torsion. The bar is rendered perfectly horizontal, and the whole is inclosed in an appropriate circular case to shield it from the air.

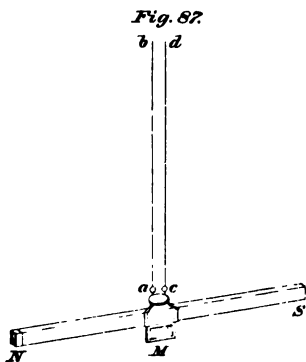
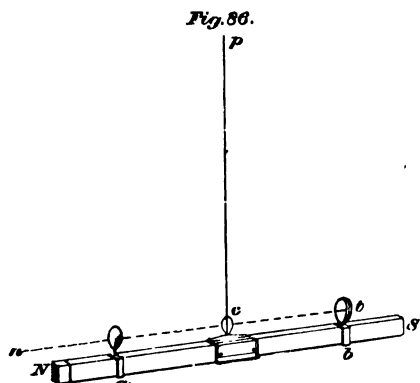
The declination of the magnet is observed with this instrument by means of a theodolite and telescope placed firmly at the distance of 8

feet, and directed in the axis of the bar, in the line of sight $n t$, through the lens a , to the cross of cobwebs in the plane glass b , and which moves as the magnet moves. We are thus enabled to record the apparent position of the magnet at any instant with respect to the reading of the divided limb of the theodolite. Now the telescope of the theodolite can be turned so as to observe the stars as they pass over the true meridian, so that the difference in the reading of the theodolite, when directed to the true meridian, and when directed to the cross of cobwebs in the magnet, is the declination of the magnet, or angles of inclination of the magnetic and true meridians, at any particular time.

We are indebted to Professor Gauss, of Gottingen, for this method of observation, by which the most minute motions of a suspended bar are rendered sensible. In fact, a magnetic bar, thus suspended and observed, is seldom seen perfectly at rest, and is, moreover, found subject to certain periodical disturbances; it becomes, therefore, requisite to watch the magnified motions, and determine from these the mean position of the bar, as the cross passes through the field of view of the telescope. To get the mean position accurately, we require at least three readings of the magnetic oscillation; the interval between the first and last reading being equal to the time of a double oscillation.

The declination magnet employed by Professor Lloyd in the Magnetic Observatory at Trinity College, Dublin, is only 15 inches in length; the glass b , Fig. 86, carries a divided scale, the true meridian is determined by a regular transit telescope, and the theodolite of observation is placed in the meridian of the transit, in a point of the plane cut by the magnetic axis of the suspended bar.

137. The horizontal Force magnet.—The object of this magnetical instrument is to measure and determine certain small changes found to occur from time to time in the directive force of the horizontal needle. It consists of a magnetic bar, $N S$, Fig. 87, similar to the former, suspended by two parallel threads of unspun silk fibers, $a b$ and $c d$; a mirror, M , is attached to the center of the bar, in which is reflected a divided scale fixed to a wall about 8 feet distant from it. The method of observation with this instrument is as follows: The suspended bar is first constrained to take an east-and-west direction, or a direction at right angles to the magnetic meridian, or



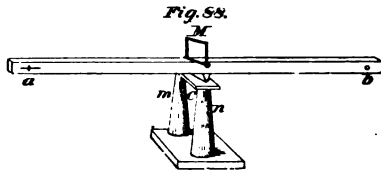
nearly so. This is effected by twisting the bifilar suspension in the way already described (115). The bar is consequently placed in equilibrium by the reactive force of the suspension with the force tending to restore it to its original position at any given instant, so that the least change in that force, whatever it be, is accompanied by a slight movement of the actual direction of the bar. Now this movement, however small, is discernible by means of a reading telescope directed towards the mirror, in which the fixed scale is reflected, different numbers of the scale being seen in the telescope, and the divisions estimated to a high degree of precision. By this instrument it is found that the magnet is drawn less towards the north at noon, and more towards evening.

In the bifilar suspension, as applied to this instrument, the torsion-circle, by which the threads are turned upon each other (115), is placed at *a c*, Fig. 87, on the brass frame or stirrup carrying the bar and mirror, and the threads of suspension pass around grooved wheels, so as to admit of the distance between them being adjusted and varied if required.

The horizontal force magnet, as employed by Professor Lloyd at Dublin, carries a light tube beneath the stirrup, in which is a lens and finely divided scale, for directing the line of sight, forming what is termed a *collimator*.

138. With a view of restraining the oscillations of the horizontal and bifilar magnetometers, the magnets are now placed within the influence of thick bars of copper, by which they are surrounded.

139. *The vertical force magnet.*—This instrument is applicable to small changes in the force by which the horizontal needle tends to take up a position more or less inclined to the horizon. A magnetic bar, *a b*, Fig. 88, is mounted on a central axis at *C*, reduced to knife edge, similar to the axis of a common balance; this axis rests on plates of agate, based on the pillars *m n* of a solid frame of brass. There are two screw-pieces, *ab*, one at each end of the bar, by which any degree of inclination in a position of rest can be changed, or the center of gravity of the whole raised or depressed. A mirror, *M*, is fixed centrally over the axis, in which is reflected a finely divided scale fixed to the stand of a telescope, directed towards the mirror, as with the preceding instruments.



The instrument being properly adjusted in the magnetic meridian, the observer sees, through a glass plate in the side of the box in which the magnet is inclosed, the divisions of the vertical scale fixed to the stand of the reading telescope, as reflected in the mirror; as the magnet inclines more or less to the horizon, these divisions and numbers on the scale are observed to change, and thus the most minute variation of the force, which causes the magnet to incline, is finally deduced. It is, for

example, found by this instrument, that at 2 a. m. the north pole is less drawn towards the horizon than at 4 p. m.

140. The magnetical instruments last described, viz, the *declination magnet*, the *horizontal force magnet*, and the *vertical force magnet*, have been set up, in various parts of the world, in magnetic observatories peculiarly fitted for their reception.

In the construction of these observatories, the presence of iron is entirely excluded, and the most elaborate care has been taken to perfect the observations. The position of the three instruments is such as not to influence each other's motions, and it admits of the observer directing his reading telescope to either instrument without changing his position. This is combined with a ready means of observing, by the ordinary astronomical methods, transits of the stars, and of determining the relative positions of the lines of the true and magnetic meridians at any given moment; there is also a complete set of corrections for changes likely to be affected in the bars from heat. Index errors and other disturbing causes have also been deduced, and thus nothing is left unprovided for requisite to an accurate result.

Observations with these instruments have been generally made every two hours, and the divisions of the respective scales, as reflected in the mirror of each instrument, duly noted; these readings are subsequently converted into measures of the changes in the declination or variation to minutes or seconds of a degree, and of the horizontal and vertical forces to thousandth parts of the whole or total force operating on the bars.

These two-hourly observations have been lately superseded in the observatory at Greenwich by a sort of perpetual registration of the instruments, by means of photography. A general idea may be formed of this process by imagining that, instead of the scale of inches being reflected from the mirrors, a narrow ray of light from a lamp is reflected, and which moves as the mirror moves, and that in this way a spot of light is made to travel upon a screen fixed so as to receive it, and over which it moves without the least friction. Conceive now that this spot of light moves upon a screen of photographic or sensitive paper, inclosed within a dark and inclosed space; and imagine the sensitive paper to be rolled round a cylinder, turning upon an horizontal axis once in twenty-four hours, then the path of the light thrown from the mirror upon the paper will be recorded from moment to moment by the discoloration of the paper in consecutive points. Finally, the impression is made permanent at the end of each twenty-four hours by removing the paper and applying the usual photographic means for that purpose. The papers thus preserved become perpetual records of the continued variation of the forces operating on the bars.

In the Greenwich observatory, the registrations of the light from the mirror of the horizontal force magnet correspond to a circle of twenty-four feet radius, and extend over five inches of the photographic scale,

so that a variation of the one-thousandth part of the horizontal force acting on the magnet will cause a deviation of the spot of light through twenty-four one-hundredths of an inch on the paper; and in the vertical force fifty-two one-hundredths of an inch are estimated in a similar way.

The magnets, lamps, and registering cylinders are shut up in long rectangular cases of zinc, and the ordinary meteorological instruments are also registered in conjunction with the magnets.

We are indebted to Gauss, a celebrated German astronomer and mathematician, for the first commencement of regular magnetic observatories fitted with instruments of this kind.

CHAPTER VI.

LAWS OF MAGNETIC FORCE.

Preliminary Observations—Experiments of Hawksbee, Brook Taylor, and Whiston—Muschenbroek's experiments—Experiments and observations by various authors—Lambert's celebrated memoirs—The memoirs and experimental investigations of Coulomb—Hanstein's researches—Theoretical and experimental inquiries by the author—Barlow's deductions and experiments on iron shells.

141. The wonderful influence of magnetism as a physical agent would necessarily lead to an investigation of the laws by which its operations are regulated. The first and most obvious step in such an inquiry would be the general law of change in the effective force of magnetism as the distance at which it acts is varied, or, in other words, to find according to what law two magnetic particles attract or repel each other magnetically as the distance between them is increased or decreased.

But, before entering upon this question, it may not be unimportant to the student to review briefly the numerical and mathematical elements essential to the progress of such an investigation.

142. We have first to observe that when any two quantities are so linked together that one of them cannot be changed in any degree without some relative change taking place in the other, then the one quantity is said to vary in some particular ratio of the other, either *directly* or *inversely*.

Suppose, for example, the power of a magnet to *increase* when that peculiar condition of its molecules which we term magnetic becomes *exalted*, or reciprocally to *decrease* when that condition becomes *depressed*, then the force said is to vary in some proportion of the magnetic intensity *directly*. In this case the two quantities both increase or decrease together. Again, the magnetic condition being the same, suppose the attractive force to *increase* when the distance of its action is *diminished*, or to *decrease* when that distance is *increased*. In this case the force is said to vary in some proportion of the distance; inversely, since one of

the quantities increases as the other decreases; or conversely, one decreases as the other increases. We may, however, as is evident, have a great variety of different relative proportions according to which such changes may ensue. It might be, for example, that when we doubled the exaltation of the magnetic condition, the force of the magnet would be also doubled, or it might be quadrupled, or increased in any other direct proportion, in which case the force would be said to vary, as the first, second, third, &c., powers of the magnetic intensity, as the case may be; and this also applies to the several inverse ratios as it respects the force and distance of its action.*

143. Taking the inverse or reciprocal proportions as being in the present inquiry well adapted to further explanatory illustration, we have to observe: First, that when the force decreases in precisely the

* Not to leave anything connected with these inquires unexplained, we venture to remark

That the successive multiplication of any given number by itself constitutes what have been termed powers of that number. Take, for example, the number 4, and multiply it by 4; then we have, adopting the common arithmetical signs, $4 \times 4 = 16$. We have here two factors producing 16; hence 16 is said to be the second power of 4, usually called the square of 4.

In like manner, again multiplying by 4, we have $16 \times 4 = 64$, which, being the same as $4 \times 4 \times 4$, gives three factors; hence 64 is termed the third power of 4, commonly called the cube of 4, and so on.

Such powers are represented by a small figure, called an index, placed at the head of the given number; thus, we may write successive powers of 4 thus—

$$4^2, 4^3, 4^4, 4^5, 4^6, \&c.;$$

thereby showing that 4 is multiplied into itself 2, 3, 4, &c., times. We may observe here, that in taking the indexes in the reverse direction, 6, 5, 4, 3, 2, &c., we should fall back upon 1, and even upon zero or 0, and hence arrive at 4^1 and at 4^0 , that is, 4 raised to the first power, and 4 raised to the power of nothing; so that 4 taken as a single factor may be considered as the first power of 4. With respect to 4^0 , or any other number whatever, raised to the power of 0, its value is always unity or 1, as is seen in any of the ordinary works of algebra. Taking a to represent any number whatever, we have hence the following series:

$$a^0, a^1, a^2, a^3, a^4, \&c.$$

When we again revert to the number from which any given power has been obtained, we are said to extract the second, third, fourth, &c., root, as the case may be. Thus, the third root of 64 would be 4, since, as just remarked, $4 \times 4 \times 4 = 4^3 = 64$; so likewise the second root of 16 would be 4, since we have $4 \times 4 = 4^2 = 16$; and the second root has been called the square root, the third root the cube root.

In like manner we have the fifth root of $32 = 2$, since $2 \times 2 \times 2 \times 2 \times 2 = 2^5 = 32$.

These roots are often represented by a fractional index, that is, by dividing the index of the power by the index of the root we wish to extract. Thus the square or second root of 3 to the first power may be expressed thus, $3^{\frac{1}{2}}$; the cube or third root of 5 by $5^{\frac{1}{3}}$, the square root of the fifth power of 2 by $2^{\frac{5}{2}}$, and so on. In this sense we are said to raise the given number to the power of $\frac{1}{2}$, or $\frac{1}{3}$, or $\frac{5}{2}$, as the case may be.

Commonly, such roots are represented by the index of the given root, placed within the sign $\sqrt{\quad}$; thus, for the cube root of 3, we write $\sqrt[3]{3}$, for the fifth root of 2 $\sqrt[5]{2}$. In thus representing the square root of any given number, the small figure for the index is commonly omitted; thus, for square root of 9, we write simply $\sqrt{9}$.

same inverse proportion as the distances increase, or, reciprocally, that is to say, if at *half* the distance the force be *twice* as great, at *one-third* the distance, *three times* as great, and so on, then the force is said to vary in the inverse simple ratio or first power of the distance, since we take the simple numbers, 1, 2, 3, &c., to represent the increase of the force. Suposing, however, that at *one-half* the distance the force becomes *four times* as great, at *one-third* the distance *nine times* as great, and so on. In this case the force would be said to vary in the inverse duplicate ratio, or second power of the distance, since, to represent numerically the increase of the force, we must multiply the numbers 1, 2, 3, &c., into themselves, taking their second powers or squares. In a similar way, cases may arise in which the increase or decrease of the force is such as to require the third power or cubes of the numbers 1, 2, 3, 4, &c., to complete the proportion. This would arise when at half the distance the force had increased 8 times, at one-third the distance 27 times, and so on. In this case the law of the force is said to be as the cubes of the distances inversely, or in the inverse triplicate ratio of the distances; and thus we may continue for any other powers of the numbers 1, 2, 3, &c., so as to express laws of force in the inverse ratio of the fourth, fifth, sixth, or any other powers of the distance, did such forces exist.

A similar reasoning applies to forces increasing or decreasing in any inverse proportion *less* than that of the mere distance, as in the case of a force becoming doubled at one-quarter the distance, trebled at one-ninth the distance. In this case the force would be said to vary inversely as the square roots of the distance, since we must take the square roots of the numbers 1, 4, 9, &c., to fulfill the proportion. In this way we express the law of force for any other roots of the distances, such as a cube, or third root, the fourth root, &c.; and since these roots are mathematically denoted by fractional indexes, we may consider such forces as being in the inverse ratio of the one-half, one-third, one-quarter, &c. powers of the distances.

We may further extend this inquiry to cases of roots of the simple or other powers, such, for example, as the square root of the cube of the distance, being, as expressed mathematically, the cube of the distance raised to the power of one-half. An inverse proportion of this kind has been termed "sesquiplicate," and would apply to a case in which, by decreasing the distance to one-half, one-third, &c., the force becomes about 3 times and 5 times as great, or very nearly. In like manner, we may obtain forces varying in the inverse ratio of the square roots of the fifth powers of the distances, termed "sesquiduplicate," and which applies to a case in which, by reducing the distance to one-half, one-third, one-fourth, &c., the force becomes increased between 5 and 6 times, and between 15 and 16 times, and 32 times, respectively. In this way almost any observed experimental results, demonstrative of any particular law of force, may be mathematically represented.

144. The particular inverse ratio comprised in a series of experimental

numerical results of this kind may be easily discovered by a slight inspection, since the forces multiplied by the simple or some other power of the corresponding distances should, in each particular case, give the same product. Thus, if at distance 12 the force were 8, at distance one-half or 6 the force became 16, we have in this case $12 \times 8 = 6 \times 16 = 96$, a simple inverse proportion; but if at distance 12 the force were 8, and at distance 6 the force became 32, then to obtain a coincident product we must take the second powers or squares of the numbers 12 and 6, and we should then have $12^2 \times 8 = 6^2 \times 32$, or $144 \times 8 = 36 \times 32 = 1152$. In the case of direct proportion the products are differently circumstanced.*

* A complete apprehension of these practical researches and proportions being essential, the following numerical examples may not be altogether uncalled for:

Let the distances be taken in some unit of measure, say tenths of an inch, and the corresponding forces in any other unit of measure, say degrees of an arc.

Suppose, as a first example, we had obtained the following results:

At distances	12	6	4
The forces are	5	10	15

Here we have the inverse simple proportions—

$$5 : 10 :: 6 : 12, \text{ and } 5 : 15 :: 4 : 12, \text{ and } 10 : 15 :: 4 : 6.$$

$$\text{Product of distances and forces} = 60.$$

As a second example, let the results be—

At distances	12	6	4
Forces	2	8	18

Here we have an inverse duplicate ratio, or square of the distance, furnishing the proportions—

$$2 : 8 :: 6^2 : 12^2, \text{ and } 2 : 18 :: 4^2 : 12^2, \text{ and } 8 : 18 :: 4^2 : 6^2;$$

that is, $2 : 8 :: 36 : 144, \text{ and } 2 : 18 :: 16 : 144, \text{ and } 8 : 18 :: 16 : 36.$

$$\text{Product of forces by squares of the distances} = 288.$$

As a third example, suppose the experimental numbers were—

At distances	16 and 4
Forces are	2 and 128

This would furnish a proportion inversely as the cube of the distance, and we should have—

$$2 : 128 :: 4^3 : 16^3; \text{ that is, } 2 : 128 :: 64 : 4096.$$

$$\text{Product of forces by cubes of the distance} = 8192;$$

and so on for other changes of distances, or any other powers.

Let now the results be—

At distances	16 and 4
Forces	3 and 6

In this case we should have a proportion in the inverse ratio of the square roots of the distances, and we should obtain the inverse proportion—

$$3 : 6 :: 4^{\frac{1}{2}} : 16^{\frac{1}{2}}; \text{ that is, } 3 : 6 :: \sqrt{4} : \sqrt{16}, \text{ or } 3 : 6 :: 2 : 4.$$

$$\text{Product of forces by square root of the distance} = 12.$$

Again, let distances and forces be thus—

At distances	27 and 8
Forces	6 and 4

145. We have been desirous to place this question before the student in a simple and intelligible form, principally on account of the great importance of such inquiries to the general progress of science and theoretical knowledge. Thus, Newton demonstrates in his great work, "The Principia," that if the particles of common matter act on each

Here we have the inverse proportion of the third or cube roots of the distances, and we obtain—

$$6 : 4 :: 27^{\frac{1}{3}} : 8^{\frac{1}{3}}; \text{ that is, } 6 : 4 :: \sqrt[3]{27} : \sqrt[3]{8}, \text{ or } 6 : 4 :: 3 : 2.$$

Product of forces by third root of distances = 12 ;

and so on for any other roots.

The following are examples of sesquiplicate and sesquiduplicate inverse proportions, being fractional powers or roots of powers.

Suppose that—

For distances	12	6	4
Forces were.....	5	14.2	26

Here the forces are in inverse proportion to the square roots of the cubes of the distances, or in inverse sesquiplicate proportion, and we obtain such a proportion as this for distances 12 and 6—

$$5 : 14.2 :: 6^{\frac{3}{2}} : 12^{\frac{3}{2}}; \text{ that is, } 5 : 14.2 :: \sqrt{6^3} : \sqrt{12^3}, \text{ or}$$

$$5 : 14.2 :: \sqrt{216} : \sqrt{1728}, \text{ or } 5 : 14.2 :: 14.7 : 41.5 \text{ nearly.}$$

Product of forces by square roots of cubes of distances = 208 nearly.

A similar proportion is evident for the remaining forces and distances.

As a last example—

Let distances be	12	6	3
And forces.....	4	2.25	128

Here the forces are in an inverse sesquiduplicate proportion, or in an inverse proportion to the square roots of the fifth power of the distances, and we obtain for distances 12 and 6 the following:

$$4 : 22.5 :: 6^{\frac{5}{2}} : 12^{\frac{5}{2}}, \text{ or } 4 : 22.5 :: \sqrt{6^5} : \sqrt{12^5}; \text{ that is,}$$

$$4 : 22.5 :: \sqrt{7776} : \sqrt{248832}, \text{ or } 4 : 22.5 :: 88.5 : 499 \text{ nearly.}$$

Product of forces by square roots of fifth powers of distances = 1996 nearly.

The numerical operations in these examples have been taken as the numbers stand, without regard to any further reduction ; but, as will be evident on examination, the arithmetical processes may be made smaller by taking the ratio of the distances and forces, instead of the distances and forces as given by experiment, when that can be done conveniently.

In cases of direct proportions the products are obtained by a method the reverse of this. We then multiply the terms crosswise, as it were. Suppose, for example, in three experiments, in which the magnetic intensity varied, we had obtained the following:

Magnetic intensity.....	1	2	3
Force.....	4	8	12

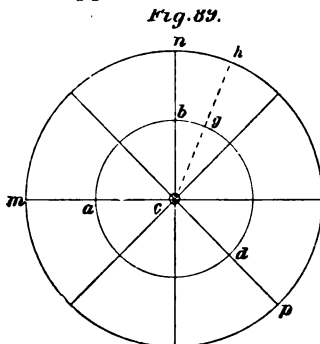
In this case of direct proportion the magnetic intensity is not multiplied into its corresponding force, but into the force of the intensity with which it is compared. Thus, comparing intensity 1 with intensity 3, we have $1 \times 12 = 4 \times 3 = 12$; or, comparing intensity 2 with intensity 3, we have $2 \times 12 = 8 \times 3 = 24$, passing on crosswise of the table. In fact, we have here $1 : 3 :: 4 : 12$, or $3 \times 4 = 1 \times 12$; also $2 : 3 :: 8 : 12$, or $3 \times 8 = 2 \times 12$; and this applies to direct ratios involving powers or roots, as before.

other with a force varying in the inverse proportion of the squares of their distances, then the sensible action of hollow or solid spheres on each other will be the same as if all the matter of which they consist were collected in their centers, and that a particle placed anywhere within them would be in equilibrio, and not tend to move in any one direction, which he shows could not be the case under any other law of force.

We may further remark in respect of magnetism that the force by which a magnetic needle is drawn towards its meridian when deflected from it, or towards a magnet, increases as the sine of the angle of the obliquity of action directly. Hence, as observed by Professor Robinson, we cannot pretend to explain the action of a magnet by the impulsion of a stream of fluid, or by pressure arising from the motion of such a stream; for in this case the pressure on the needle must have diminished directly as the square of the sine of the angle at which the magnetic force operates on the needle. For example, the force at a right angle, or 90° , should be four times greater than the force at an angle of 30° , whereas it is found to be only twice as great, being simply as the sines of the angles. It is therefore by the determination of the laws of such forces that we are enabled to advance our knowledge of the powers of nature.

146. Besides these preliminary explanations there remain still to be considered one or two additional points equally essential to an intelligible and plain view of the questions involved in such inquiries, and the real sense in which we are to accept such expressions of the law of variation of certain forces as we have just cited.

To suppose any effect to be as the square or cube of its cause, either directly or inversely, is to suppose the effect to proceed partly from the cause and partly from nothing. For there is no axiom in physics more evident than that which assigns between cause and effect a simple relation; any expression, therefore, which represents a force as being in any inverse ratio of a power of the distance greater than unity, may at first appear to involve an absurdity. We may hence infer that, when



by experiment we have arrived at such a conclusion, the result is either a mixed result, compounded of two or more conjoined actions, or it is a result resolvable into some elementary condition of a simple kind, depending on the peculiar kind of agency upon which the exhibition of force depends. Take, for example, the following case of a central force, or emanation of any kind, extending its power in all directions into space, and hence becoming weaker in proportion to

the surface of the spaces over which we may suppose it to expand.

Let c (Fig. 89) represent such a central action; suppose, for example, a central source of light considered as luminous matter, by way of illustration. Let $a b d$, $m n p$, be two great concentric circles, representing two concave hemispherical shells, whose center c is the point of illumination, and whose radii $c a$ and $c m$ are to each other as 1 : 2; or, in other words, that the point n is twice as far from the center c as the point b . If in this case we take any two homologous segments, $b g$, $n h$, of these shells, it is clear that the segment $n h$ will have four times the area of the interior similar segment $b g$; because the superficial areas of such shells will be in proportion to the squares of the diameters of their great circles $m n p$, and $a b d$, and these are supposed in this case to be as 1 : 2; so that the quantity of luminous matter (supposing light to be a material agency) which has emanated from the center c , and fallen upon these shells, will in the outer shell n become distributed over 4 times the space it would occupy on the interior shell b ; that is to say, in any one point there will be only one-fourth the quantity of light; hence the illumination of the arc $n h$ will only be one-fourth of the illumination of the arc $b g$; that is to say, the illumination will be directly as the quantity of light in a given space—a simple relation of cause and effect. When, however, we refer this effect to the distance from the center c , we perceive that the distances being as 2 : 1, the illumination of the whole of each shell is as 1 : 4. And thus light as a physical agency has been said to vary in intensity in the inverse ratio of the squares of the distance from the center, in the way just explained; but the fact is that the illumination of an equal area in each shell is directly as the quantity of the agency producing it.*

147. Again, in the cases of such powers as those of magnetism and electricity, we have to consider many conjoint actions. A magnet and common iron only operate on each other through the medium of a reciprocal induction; when we change the distance of their action we change at the same time the original condition or quantity of force in operation; so that we may conceive the total force of attraction to depend on the force induced in the iron conjoined with the reciprocal induction on the magnet; and it may be here remarked that in the apparent anxiety of philosophers to bring such forces indiscriminately under the common law of gravity and other central forces, they have probably encouraged a rather hasty generalization. All the forces in nature are

*The term intensity is really inapplicable here; it is a term, in science, only distinctive of quality, or of different states or degrees of power of the same agent; as when we say the heat of a red-hot iron is more intense than the heat of boiling water, or that moonlight is less intense than the light of the sun. Taking a particle of light from the same source, we have no reason for supposing it in a different state of intensity at different distances from the center of illumination. If such were the case, both the quantity of light in a given space, and its intensity also, would change with the distance, and the illumination would then decrease much faster than that of the inverse squares of the distances.

not necessarily central forces; they may arise out of peculiar conditions of common matter, of which we have as yet but an indistinct notion, and be exerted between given points in determinate directions only, as appears to be indicated in Fig. 16. We have yet to learn, therefore, whether the force of magnetism comes under the general conditions of ordinary central forces or not.

148. Newton, in "The Principia," considers magnetic force as being very different from that of gravity: "The magnetic attraction is not (he says) as the matter attracted; some bodies are attracted more by the magnetic, other less; most bodies not at all. The power of magnetism in one and the same body may be increased and diminished, and is sometimes far stronger for the quantity of matter than the power of gravity, and, in receding from the magnet, decreases not in the duplicate, but almost in the triplicate proportion of the distance, as nearly as I could judge from some rude observations."—Book III, prop. 6.

In the twenty-third proposition of the second book, section 5, Newton imagines that, in magnetical bodies "the attractive virtue is terminated nearly in bodies of their own kind that are next them." "The virtue of the magnet," he says, "is contracted by the interposition of an iron plate, and is almost terminated at it, for bodies farther off are not so much attracted by the magnet as by the iron plate."

149. Of the early experiments instituted with a view of determining the laws of magnetic forces, we have to notice first those of Hawksbee. A short needle, one inch in length, being poised on a fine point, fixed in the center of a graduated quadrant, a natural magnet was placed with one of its poles within certain measured distances of the center of the needle, and the corresponding deviations of the needle from the meridian, noted in a way similar to that described, section 117, Fig. 79. The results have not generally been considered very satisfactory or regular; it is, nevertheless, worthy of remark that, taking the tangents of the angles of deviation, corresponding to distances, which may be considered as very great in respect of the length of the needle, on the principles already laid down, then Hawksbee's result will be found consistent with each other, and, according to a law of force, varying in the inverse sesquiduplicate ratio of the distances, as shown in the following analysis of the results:

Distance in inches...	12	18	24	30	36	42	48	54	60
Angles of deviation...	69	43-30	24	13-30	8-45	5-30	3-50	3	2-30
Tangents of deviation.	2.6	.948	.445	.240	.153	.096	.067	.052	.043

Taking these tangents as representing the forces, they will be found all very nearly in the inverse proportion of the square roots of the fifth powers of the distances, in some cases precisely.*

* In such experiments as these we must recollect that angles do not enter into ordinary calculation, except through the medium of certain lines taken to represent them. These lines have been termed sines, tangents, secants, &c. It may not be out

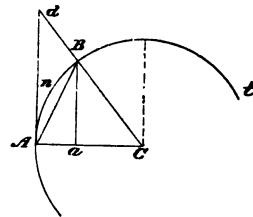
Dr. Brook Taylor, in following up this method of experiment, was led at first to infer "that the power of magnetism does not alter according to any particular law of the distances, but decreases much faster in the greater distances than in the nearer ones." By subsequent and similar experiments, however, instituted by Whiston, Brook Taylor, and Hawksbee, conjointly, "the attractive power of the loadstone was found in inverse sesquiduplicate ratio of the distances." In these experiments they measured the forces by the sines of half the arcs of deviation, to which they endeavor to show the "force is always proportional."

150. About this period, experimental philosophy began to make considerable advances in Holland, and to excite very general interest; we consequently find the Dutch philosophers contributing largely to our knowledge of this branch of physics. The celebrated Muschenbroek instituted some experiments in 1724, the object of which was to find experimentally the law of magnetic attraction by the method of weights.

of place to recall briefly to the student's attention the nature of the two lines with which we are here especially concerned, viz, the tangent and sine of an angle.

Every angle $A C B$ (Fig. 90) is measured by an arc $A n B$ of a circle $A B t$, contained between its sides, and described from its point or vertex C as a center; the line $A B$, joining the extremities of the arc, being called the chord of the arc.

Fig. 90.



Now, a perpendicular line $B a$, drawn from the extremity B of the radius $C B$, forming one of the sides of the angle, directly upon the other side $C A$, has been termed the *sine of the angle* $A C B$; the length of this line, as is evident, will be a greater or less as the angle $A C B$ is greater or less.

Again, the line $A d$, drawn perpendicular to the radius or side $C A$, upon the extremity A , and meeting the side $C B$, continued on to meet $A d$ in the point d , has been termed the tangent of the angle $A C B$. This line also will increase and decrease with the magnitude of the angle.

If the radius $C A$ be taken as unity, and be supposed to be divided into any number of parts, say 1,000, or 100.00, or 10,000, then these lines, as applying to a given angle, will be found to contain a certain number of these parts. Thus, if we call radius $A C = 1$, or unity, and divided, say, into 100 parts, then if the angle $A C B$ be 30° , the sine $B a$ will be one-half the radius $A C$, will contain 50 of these parts, and will be represented by .5; the tangent $A d$ will, in this case, contain about 57 parts, and will be represented by .57. Now, it is these numbers, as calculated and arranged in tables, with which we have to do, and not immediately with the angles themselves.

Comparing distances 12 and 24, which are as 1 : 2, we have—

$$2.6 : .445 :: 2^{\frac{1}{2}} : 1 :: 5.65 : 1, \text{ or } 5.65 \times .445 = 2.6, \text{ or } 2.5 = 2.6 \text{ nearly.}$$

Take, again, distances 12 and 18, which are as 2 : 3; here we have—

$$2.6 : .948 :: 3^{\frac{1}{2}} : 2^{\frac{1}{2}} :: 15.5 : 5.65, \text{ or } 5.65 \times 2.6 = 15.5 \times .948 = 14.6 \text{ nearly.}$$

In a similar way, the products for distances 30 and 60 are .240 = .246; for distances 12 and 36 we have 2.4 = 2.6, which may in each case may be considered as sufficiently near.

The greatest inequality appears to be for distances 18 and 54, being .948 = .814; all the others approach as nearly an inverse sesquiduplicate ratio as can be expected from the nature of the experiment.

Having suspended a spherical magnet from one arm of a balance, and poised it by weights suspended from the opposite arm, he placed a similar magnet immediately under it, and then proceeded to find the additional weights requisite to balance the attractive force at given distances between the opposed poles. These distances were regulated by raising or depressing the beam of the balance by means of a line passing over a pulley, and by which it was supported. The numerical results of the experiments were considered so unsatisfactory as to lead to the conclusion that "no assignable proportion" exists between the forces and the distances, whether of attraction or repulsion, and that "magnets are indeed very surprising bodies, of which we know but little."

151. In the "Introduction to Natural Philosophy," however, by

Fig. 91. Muschenbroek, we find the subject more satisfactorily investigated and pursued, the results being such as to demand very special attention. The method of experiment did not materially differ from the former. The following cases comprise the amount of the investigation:

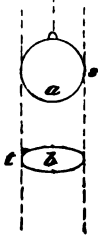


First case.—Attractive force between a magnetic and iron cylinder.—In this experiment a cylindrical magnet (*p*, *Fig. 91*), 2 inches in length, and about .95 of an inch in diameter, was suspended over an equal cylinder of soft iron (*n*), and the attraction at different distances (*p n*) noted. The results were as follow:

Distances, in tenths of an inch.....	6	4	3	2	1	0
Force, in grains	3	5	6	9	18	57

Muschenbroek observes, on this experiment, that the attractive forces

Fig. 92. are inversely as the intercepted cylindrical spaces (*p n*), that is, inversely as the distances; the law is uniform up to contact, or nearly so.



Second case.—Attraction between a spherical magnet and a magnet cylinder.—In this experiment a spherical magnet (*s*, *Fig. 92*) was suspended with its north pole (*a*) downward, and a cylindrical magnet (*t*) of the same diameter, viz, .95 of an inch, placed with its south pole (*b*) upward, immediately under it, the poles being in one straight line. The following were the results:

Distance, in tenths.....	6	4	3	2	1	0
Force, in grains.....	21	34	44	64	100	260

We may conceive, says Muschenbroek, "The sphere (*s*) to be in a hollow cylinder (*t s*), and let down at various distances (*a b*) from the cylindrical magnet. Then, considering the intercepted spaces (*t s*), the attractions will be found in the inverse sesquuplicate ratio of these spaces, that is, inversely as the square root of the cubes of the spaces." In referring the distances, however, to the near point *a* of the sphere,

still the law does not very materially differ from the former case, being approximately in the inverse simple ratio of the distance $a b$.

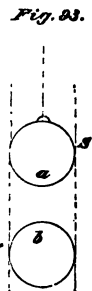
Third case.—Attraction between a magnetic sphere and a cylinder of iron of the same diameter, = .95 of an inch.—In this experiment a cylinder of iron (b , Fig. 92) was placed under the north pole (a) of the spherical magnet (s), this cylinder being the same as used in the first case. The following were the results:

Distance, in tenths	6	4	3	2	1	0
Force, in grains.....	7	15	25	45	92	340

Muschenbroek, in referring the forces to the intercepted spaces ($t s$), as before, deduces the same law as in the former case; if, however, we refer the forces to the distance $a b$, we find no regular law. The first three forces are inversely as the squares of the distances, or very nearly. The forces corresponding to distances 4 and 2 are in the inverse sesquuplicate ratio of the distances; this is also evident at distances 6 and 1. At the smaller distances 2 and 1 the force is inversely as the simple distance, very nearly. At distances 6 and 2 no law is apparent.

Fourth case.—Attraction between a magnet and iron sphere of equal diameters.—In this experiment a globe of iron (b , Fig. 93) was placed immediately under the north pole (a) of the suspended spherical magnet (s). The forces and distances in this case stood thus:

Distance, in tenths.....	8	6	4	3	2	1	0
Force, in grains.....	1	3.5	9	16	30	64	902



It is remarked by Muschenbroek, in this case, that if “we suppose both the spheres to have been included in a hollow cylinder ($t s$), and to be removed from one another at various distances, and the intercepted hollow spaces ($t s$) to be considered, then we find the law in a reciprocal biquadratical ratio of the intercepted spaces, that is, inversely as the fourth powers of the intercepted spaces. If, however, we refer the forces to the nearest points of distances $a b$, we have all sorts of inverse proportions for the law of the force; thus the forces at distances 8 and 4 are inversely as the third power, or cubes, of the distances, or very nearly; at distances 8 and 1 they are inversely as the second power, or square, of the distance; and this law holds approximately for the forces at distances 6 and 4, and for 6 and 3, for 6 and 2, and 4 and 3, in which last case it is exact.”

At distances 8 and 2 the forces are as the square roots of the fifth powers of the distances inversely. Taking the near distances 2 and 1, we have the forces nearly in the simple inverse ratio of the distances; whilst at the distances 6 and 1, as also 4 and 2, the law approaches the inverse sesquuplicate ratio of the distance, that is, the square root of the cubes of the distances.

152. These results are not only curious, but they are really calculated, when properly considered, to throw very considerable light on the nature and mode of operation of magnetic force, as we shall presently see;

and it is to be greatly regretted that more attention has not been commonly bestowed on them. Muschenbroek's researches are usually quoted without due precision, and without any adequate explanation of the author's own peculiar deductions; they have been also not unfrequently treated lightly as furnishing no solid information whatever from assumed imperfections in the nature of the experiments themselves.

153. We may infer, by the second and third cases, in which the force at contact between a cylindrical and a spherical magnet, and the force between a similar cylinder of iron and the same spherical magnet, is given, that, when actually touching, a magnet does not attract another magnet so forcibly as it attracts simple iron, the force being, in the one instance 260 grains, in the other 340 grains. The force, however, between the two magnets diminishes less rapidly as the distance is increased, and would hence begin from a more remote point.

154. In the "Essai de Physique," printed at Leyden, in 1751, Muschenbroek more expressly refers to his early experiments in 1724, and although they led to no general conclusions, yet they furnish most important examples of the operation of magnetic forces under the given conditions. The following table, for example, contains the results of a series of observations on the force of two spherical magnets of very unequal diameters, opposed to each other at dissimilar poles, as in Fig. 93, one of the magnets being 6.5 inches in diameter, the other 1.5 inches.

Distance, in lines—

54 50 45 28 21 12 10 9 8 7 6 5 4 3 2 1 0

Force, in grains—

1.75 2.25 2.75 9 12 26 31 34 36 39 44 48 59 68 89 132 310

Many of these forces approach the inverse sesquuplicate ratio of the distances. It is, however, observed by Muschenbroek, that, from the unequal diameters of the spheres, "it is not easy to calculate the intercepted spaces; this led me to try the forces between a spherical magnet and a ball of iron, each .95 of an inch in diameter." The attractions as thus obtained, have been already given. Fourth case (151).

The following are the results of observations on the repulsive poles of two magnets, and of two pieces of magnetic iron :

REPULSIVE FORCE OF TWO MAGNETS.

I.								
Distance, in lines	48	27	12	11	10	9	8	
Force, in grains	6.5	13	30	32	32	33	34	
II.								
Distance, in lines	12	10	6	5	4	0		
Force, in grains	24	24	25.5	27.5	29	40		

REPULSIVE FORCE OF MAGNETIC IRON.

III.								
Distance, in lines	12	10	6	5	4	3	2	1 0
Force, in grain	3.5	4.25	7.5	7.75	8	10.5	14.5	14 Attn.

It is important to observe, in these last experiments, that in the first forces and distances, the force is as the distances inversely, after which the increase of the repulsion decreases, and the force changes into attraction. We have thought it right to select these cases for consideration. For, notwithstanding that they led at first to the conclusion "that magnets are surprising bodies, of which we know but little," they will, nevertheless, be found to have a most important bearing on the question of magnetic force.

155. Martin, who followed Muschenbroek's method of experiments, found that for certain small distances the force of a magnetic pole on a bar of soft iron was in the inverse sesquiplicate ratio of the distance. In these experiments a plate of wood, of a thickness equal to the required distance, was interposed between the suspended magnet and iron. The magnetic pole being allowed to rest on the wood, and to which it would become drawn by the reciprocal attraction between the iron and magnet, small weights were then added to the scale-pan attached to the opposite arm of the balance, until the magnet pole became raised off the wood. The actual force and distance were as follows:

Distance, in inches.....	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$
Force, in grains	156	58	28

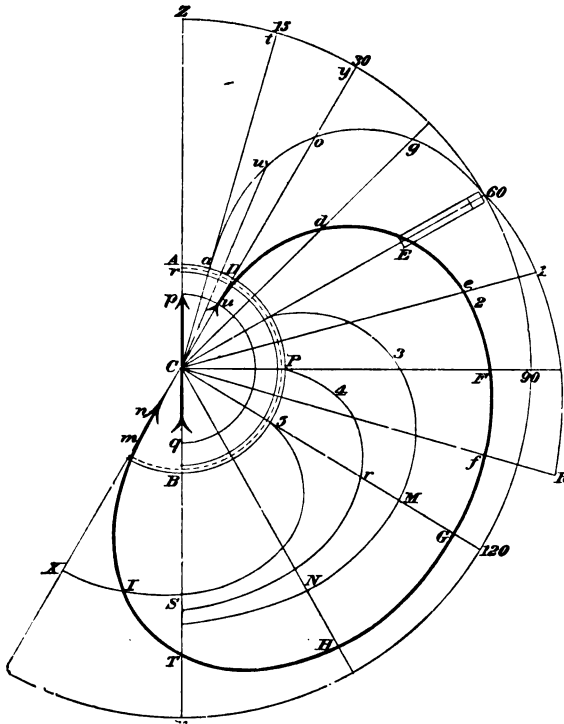
It will be immediately perceived that these forces are inversely as the square roots of the cubes of the distances, very nearly. Taking the distances as the numbers 1, 2, 3, we have $1 \times 156 = 2^{\frac{3}{2}} \times 58 = 3^{\frac{3}{2}} \times 28$; the differences in the products, viz, 156, 164, and 145, are not so great as to place them without the limit of a fair approximation, especially when we take into account the difficulty of such experiments. If at distance $\frac{1}{2}$ the result had been 56 grains instead of 58, and at distance $\frac{1}{3}$ it had been 30 grains instead of 28, then the ratio would have been exact. The experiments appear to have been carefully made.

156. Mayer, in an unpublished paper read before the Royal Society of Gottingen, in 1760, found the force of magnetic attraction to correspond with the general law of gravity. A deduction also arrived at by Michell, who says, in his capital treatise on "Artificial Magnets," published in 1750, that in all the experiments of Hawksbee, Brook Taylor, and Muschenbroek the force may really be in the inverse duplicate ratio of the distances, proper allowance being made for the disturbing changes in the magnetic forces so inseparable from the nature of the experiment. He is hence led to conclude that the true law of the force is identical with that of gravity, although he does not set it down as certain.

157. In volume 22 of "Histoire de l'Académie Royale des Sciences" (Berlin, 1776), we find two beautiful memoirs on this subject by M. Lambert, which were considered by Dr. Robison as worthy of Newton himself. In his first memoir the author endeavors to determine two very important laws of magnetic action; one relating to the change of force as depending upon the obliquity of its application, the other as referred to the distance. M. Lambert's course of experiment was as follows:

A small needle ($p q$, fig. 94), about an inch in length, being poised on a fine center (C), fixed in a plane of wood, a circle ($A P B$), one-half of which only is in the figure, was described about the needle, and divided into 180 degrees, both on the east and west side of the magnetic

Fig. 94.



meridian ($x C z$), the central or north point (A) of the semicircular arcs being marked zero; the plane supporting the needle was made to turn about the center (C), so as to adjust the zero point (A) exactly in the line of the needle. This preparation made, Lambert placed a small magnet (E) of a cubical figure, the same length and breadth as the needle, and one-half the thickness, in various positions, $E, e, F, f, G, \&c.$, about the needle, so as to deflect it from its meridian by a given angular quantity. We already know that in bringing a mag-

net near a compass-needle in this way the needle changes its position, so that, by varying the position of the magnet, we may produce any declination we please; we may also give the magnet (E) an infinity of different positions, or may change its place, as from $D, F, G, H, \&c.$, and hence may find such positions or points for its action as will all produce the same degree of declination in the needle. Now M. Lambert limited the precise position of the magnet in any particular point (E) to that in which the axis of the magnet and its south pole were directed to the center (C) of the needle, as in the line EC ; and he selected given declinations of the needle from 10° to 100° on the west side of the meridian, and from $15, 30, 60, 90$, up to 120 degrees on the east side. Having found all the points, as, for example, $D, d, E, e, F, f, G, H, I, \&c.$, in which the magnet (E), thus circumstanced, gave the same amount of declination, say 30° , he proceeded to trace a curve ($D E F G H I m$) through all these points, and by means of which he endeavors to assign the law of force as directed to the center (C).

158. For the better tracing the various circle and curves, the plane on which this operation was performed was covered with fine paper.

The figure is about three-fourths of the size of the plane in the actual experiment; and as the curves on each side of the meridian $z C x$ were found to be nearly similar, those on one side only are given, in order to avoid complication. In Fig. 94, then, C is the center upon which the needle plays, $x C z$ is the magnetic meridian. The angles $A C a$, $A C D$, $A C E$, $A C F$, $A C G$, are angles of 15, 30, 60, 90, 120 degrees, being the respective constant declinations producing the curves 1, 2, 3, 4, 5. Thus the magnet being in curve 2, the declination of needle was always 30° ; when in curve 3, it was always 60° ; and so on. By this arrangement an equilibrium is obtained between three forces, viz., the magnetic force of the needle; the directive force, or unknown power by which it is drawn to the meridian $A B$; and the force of the magnet (E) by which the needle is deflected or drawn from its meridian.

159. In comparing the curves thus obtained, Lambert only assumes, what in fact is shown by all experience, that the magnetic force decreases when the distance at which it operates increases. In estimating the element of distance, he finds it sufficient to take the distance between the extremity (E) of the magnet and the center (C) of the needle. So that, if it be merely required to know if the force of the magnet has been more or less great in one point than in another, as, for example, in points E and F, then the right lines $C E$, $C F$ will be sufficient for that purpose, and the force of the magnet may be taken as being less as these lines are longer.

160. With a view to simplify our conceptions of M. Lambert's investigations, we will confine our references principally to one of the curves which he traced, viz, to the curve No. 2, corresponding to a declination of 30° , and which caused the needle ($p q$) to assume the direction $n C u$, making, with the meridian $z C x$, the angle $z C y = 30^\circ$. It may be here observed that if we take, on either side of the radius $C G$, any two points, F, H, making equal angles $G C F$, $G C H$ with that radius, and suppose the magnet to be in F, and attracting the north pole (p) of the needle with a force $= p$, and repelling the south pole (q) with a force $= q$, then we have only to place the magnet in H, and it will reciprocally employ force $= p$ to repel the south pole, and the force $= q$ to attract the north pole; that is to say, the distances $G H$ and $G F$ being equal, position of the needle would not vary; and reciprocally, in order not to vary, these distances must be equal. The curve $D E F G H I m$, therefore, is similar to itself on each side of the right line $C G$, so that $C G$ is an axis or diameter of that curve, and divides it into two similar and equal parts, that is, supposing a perfect resemblance and equality of force in both poles of the magnet. Mr. Lambert calls this axis $C G$ a transverse axis or diameter, because it passes through the center at right angles to the deflected position of the needle. Thus, when the magnet (E) is in the curve $E G H$, just mentioned, the deflection being 30° , the position of the needle is the line $m C D$, and the axis is $C G$, and so for any other curve; thus, when the deflection is 60° , and

the needle is in the line C E, then the axis of the curve is C N, being always at right angles to the direction of the needle. We may further observe, that all the curves extend themselves from the center up to the points by which their respective diameters pass, as at X S N G R.

161. These experimental conditions of Lambert's investigations being understood, we may proceed to his analysis of them; and first, as relates to the change of force liable to occur from a greater or less degree of obliquity in the action of magnetism on the needle, considered as a lever, a most important element in the progress of such inquiries. Assuming, as we have just shown, that it requires everywhere the same effective force to retain the needle at the same declination, we might conclude, conversely, that for the same degree of declination the distance should be always the same; but such is evidently not the case, since the points D, E, F, G, &c., in curve No. 2, are all at different distances from the center (C); hence all the force of the magnet (E) cannot be everywhere exerted; some compensation between the force and distance must hence arise, if the needle at different distances is to remain in the same position. Now we may observe, that in different points of a given curve D E F G H, the action of the magnet (E) is more or less oblique upon the needle ($p q$); thus, the needle being retained in the line $n u$, at a deflection of 30° , the angle of obliquity at point E is E C D, at point F it is F C D, at point H it is H C D; that is to say, the obliquity of the action increases with the distances. In order, therefore, that the needle should remain stationary, the decrease of the force due to the increase of distance should be exactly the same as decrease of power arising from the increased obliquity of the action. To determine the law of the change of force from obliquity, Lambert calls to his aid the polar or magnetic force by which the needle is drawn toward the meridian, and which also acts obliquely upon the needle whenever we deflect it from its meridian. Thus the needle ($p q$) being drawn from its meridian into the line $n u$, the oblique action of the polar force is the angle $z C y$. To distinguish in certain cases the oblique action of the magnet (E) from this last obliquity, he calls the angles of obliquity of the magnet (E) angles of incidence. Thus, angles E C D, F C D, &c., are angles of incidence as regards the obliquity of magnetism in the action of the magnet (E) on the needle. If the law of the variation of the force as regards a change of distance were really known, we could easily determine the law of the increase or decrease of force as depending upon obliquity of action; for the effect depending on this obliquity of incidence would be in the same curve in an inverse ratio of the force, in order that the compound resulting effect might retain the needle in the same position; but Lambert had not determined this law, and is hence led to another method by taking into consideration the action of the polar force on the needle.

162. To determine the effect of obliquity, considered as depending

upon the angle of obliquity, that is, as being some function* of that angle, Lambert took two equal distances (Cd and Cr), in which the absolute force of the magnet, independent of obliquity, might be considered the same. We may here observe that when the magnet is in point d , the needle is found in direction Cu , being, by the experiment for that point, deflected 30° . The angle of incidence dCu is therefore 15° , and the obliquity of the polar force is the angle $zCy = 30^\circ$. Again, the magnet being in r , the needle is in direction CF , being, by the experiment for curve 4, deflected 90° . In this point, then, angle of incidence of magnet is $FCG = 30^\circ$, and angle of obliquity of polar force $zCF = 90^\circ$. Let now the whole magnetic polar force $= M$, and the whole force of magnet $= m$; then, because the needle is at rest, either the whole or some part of the magnetic polar force must be in equilibrio with the whole or some part of the force of the magnet; and as these forces will depend upon the angle of obliquity, we have for points d and r , calling the function we require $= f$, the following equations:

$$M \times f 30^\circ = m \times f 15^\circ, \text{ and } M : m :: f 15^\circ : f 30^\circ \text{ for point } d,$$

$$M \times f 90^\circ = m \times f 30^\circ, \text{ and } M : m :: f 30^\circ : f 90^\circ \text{ for point } r. \dagger$$

But between these four functions, in the proportions thus deduced, we obtain

$$f 15^\circ : f 30^\circ :: f 30^\circ : f 90^\circ.$$

Now this proportion leads at once to the value or nature of the function required $= f$, since in the ordinary trigonometrical calculations and tables we find that the sines of these angles fulfill the conditions of this proportion. In fact, we have $\sin 14\frac{1}{2} : \sin 30^\circ :: \sin 30^\circ : \sin 90^\circ$, that is, $.250 : .5 :: .5 : 1$, which is sufficiently near for our purpose, and leaves little or no doubt as to the nature of f .

* This term *function* is in very common and accepted use in physico-mathematical science. It is employed to express, either algebraically or otherwise, any quantity whose value depends upon that of another. Thus the extent of the circumference of a circle will depend on the length of the radius of the circle. The circumference is hence said to be a function of the radius. In the present case the effective force of the magnetic power will depend upon the angle of incidence. It is hence said to be a function of that angle; so that we have to find what is the actual value or relation of this function to the magnetic power.

† The student will easily see that, to represent the equilibrium of the forces in operation, we must multiply the total magnetic force by the function of the angle of obliquity at which the force acts, and upon which the modification of the whole force depends. Thus, suppose that when the obliquity of action was a given quantity, that only one-eighth part of the total force, for example, was effective in retaining the needle at a given deflection, we should, in this case, express it by one-eighth of M , calling generally the magnetism M ; that is to say, we should multiply M by one-eighth. But since we do not know what portion of the total forces are in operation, we are content to represent it by some function of the angle of obliquity; and, therefore, in the above, write $M \times f 30^\circ$, or $m \times f 15^\circ$, as the case may be. It is further evident that, in the equilibrium of these forces, we have in all cases some portion of the total polar force acting at a constant distance in equilibrio, with some portion of the total force of the magnet acting at variable distances from the needle; hence we write, in the cases quoted,

$$M \times f 30^\circ = m \times f 15^\circ, \text{ and } M \times f 90^\circ = m \times f 30^\circ.$$

163. From this investigation, then, we may conclude that the action of magnetism on a magnetic needle, considered as a lever, is proportionate to the sine of the angle of obliquity of its direction; and that hence the effective force which operates in restoring the needle to its meridian, when drawn aside from it, is directly as the sine of the angle of its deflection—an important deduction. “If,” says Robison, “M. Lambert’s discoveries had terminated here, it must be granted that he had made a notable discovery in magnetism.”

This important result was fully established by a variety of other experiments. Thus, taking other points f and g , equally distant from center (C), or very nearly so, we have the angles of incidence $g C a = 30^\circ$ and $f C D = 75^\circ$; the needle for curve 1 being deflected 15° in direction $C a$, and for curve 2 being 30° in direction $C D$. The obliquities of the respective polar forces are consequently $z C t = 15^\circ$, and $z C y = 30^\circ$.

Whence we obtain for points g and f the two following proportions:

$$m \times f^n 30^\circ = M \times f^n 15^\circ, \text{ which gives } m : M :: f^n 15^\circ : f^n 30^\circ;$$

and

$$m \times f^n 75^\circ = M \times f^n 30^\circ, \text{ which gives } m : M :: f^n 30^\circ : f^n 75^\circ.$$

From these four functions we have, by the ordinary rules,

$$f^n 15^\circ : f^n 30^\circ :: f^n 30^\circ : f^n 75^\circ;$$

that is,

$$\sin 15^\circ : \sin 30^\circ :: \sin 30^\circ : \sin 75^\circ;$$

or

$$.2589 : .5 :: .5 : .966.$$

And $.2589 \times .966 = .5 \times .5$, or $.250 = .258$, which is a sufficiently close approximation.

164. Having thus determined the first and apparently the most simple law of magnetism, Lambert proceeds to apply it in his further investigations of the law of force as regards distance. With this view, let the total polar force which draws the needle to its meridian be considered as unity or 1, and suppose that the magnet (E) being in some point of the curve $D E G$, the needle is deflected 30° , and is in the direction $C D$. In this case the sine of 30° being $.5$, the effective polar force becomes represented by $1 \times .5$; that is to say, it may be expressed by $.5$. Now, the needle being stationary, in whatever point of curve 2 the magnet be placed, it is clear that the oblique or effective force of the magnet in any point d, E, e must be equal also $.5$, because in these points it exactly balances the polar force.

Now, let the actual or inherent force of the magnet at any distance $C E, C G$, &c. $= m$, and call the angle of incidence or obliquity of its action $= \varphi$; then we have the effective force in every point of the curve $= m \times \sin \varphi$; but as this force, as just shown, must be $= .5$, we have therefore by these two values

$$m \times \sin \varphi = .5, \text{ and } m = \frac{.5}{\sin \varphi}.$$

Taking now the different angles of incidence $d C D, E C D, e C D$, &c. for the successive points d, E, e , &c., and which are by construction 15° ,

30, 45, 60, &c., up to 120° , and dividing .5 by the sines of these angles, we obtain the value of m , or absolute force of the magnet in each point of the curve at a measurable distance from the center (C); consequently, in laying off the respective distances C D, C d , C E, &c., upon a given scale, we have the respective values of the force and distance represented by numbers. M. Lambert estimates the distance in terms of a unit of measure = $\frac{1}{2}$ the length of the needle. The forces and distances thus determined will be as in the following table: *

Points of curve.....	d	E	e	F	f	G
Distances = d	2.71	3.62	4.17	4.33	4.48	4.61
Forces = f	1.93	1.00	0.7	0.57	0.51	0.5

165. It will be observed, that in comparing these distances and forces as before, there is a general approximation to the law of the inverse square of the distance, more especially in the points F, f , G, in which the products of the forces, multiplied by the squares of the respective distances, are 10.6, 10.2, 10.6; the nearer points, however, as d , E, e , give the products 13.87, 13.10, 12.1, which exhibit greater differences. M. Lambert, however, goes on to observe that the distances here given are taken between the extremity of the magnet (E) and center (C) of the needle, that these may not be the true distances of the magnetic action, still he prefers letting the numbers remain as they are in the table, and subject them to such calculation as may be found requisite, merely bearing in mind that whatever be the true distances, they must be in some inverse ratio of the forces.

166. Supposing magnetism to be a species of central force, analogous with the force of gravity, it would then come under the same general law as regards the distance of its action, and would be in the inverse duplicate ratio of the distance. Assuming this to be the case, we may obtain the true distances corresponding to the forces by means of the general expression for this law. Thus, let f = the effective force of the magnet in points d , E, e , F, &c., and let the true distance of action we require to find = Δ ; then we have

$$f = \frac{1}{\Delta^2}, \text{ and, consequently, } \Delta = \frac{1}{\sqrt{f}}$$

If, therefore, we extract the roots of the numbers in the preceding table, represented by f , we shall, in carrying out the operations indicated in the above formula, obtain a series of numbers which, although not equal to the true distances, will still vary in the same direct ratio, and which may become equal to the true distances if multiplied by some constant

* This way of noting the results of the experiment is not the same as that adopted by M. Lambert, who gives several distinct and elaborate tables, which, in a rudimentary work of this kind, could not well be introduced. It became requisite, therefore, to simplify them, and bring the results under a less complicated form. No alteration, however, has been made in the course followed by the author, or in his numbers, which are given as found in his table.

= C, so that, in representing these numbers by δ , we should have $\Delta = \delta \times C$.*

Subjecting, then, the forces f to the indicated operation $\frac{1}{\sqrt{f}}$, we obtain, for the respective points d , E, e , F, &c., the following proportionate distances:

Points.....	d	E	e	F	f	G
Proportionate distances= δ	0.719	1.00	1.189	1.316	1.39	1.414

M. Lambert deduces for the mean value of the constant, by which these numbers must be multiplied, $C = 2.2$, as given from the whole series of experiments in the successive curves 1, 2, 3, 4, 5 (Fig. 94). The true distance, therefore, will be represented by $\Delta = \delta \times 2.2$; so that, by comparing the product of the above numbers by 2.2 with the measured distances = d , as given in the preceding table, we immediately arrive at the required correction, if any.† Take, for example, the numbers in the preceding table at points d and G; then we have for Δ , that is, the true distance,

$$0.719 \times 2.2 = 1.58 \text{ for point } d,$$

and

$$1.414 \times 2.2 = 3.11 \text{ for point G.}$$

But the measured distances for these points = d , as given in the former table, are

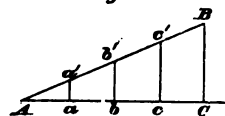
$$d = 2.71 \text{ for point } d,$$

and

$$d = 4.61 \text{ for point G.}$$

*Although a given quantity may change in the same proportion as another and greater quantity, yet we cannot ever consider the two quantities as equal. To com-

Fig 93.



plete the equality, it becomes requisite to multiply the lesser quantity by some constant number. Take, for example, the right-angled triangle A C B, and suppose it divided by parallels $a a'$, $b b'$, $c c'$, &c., and in such way, for example, that distance A a from the vertex (A) is twice the length of the parallel $a a'$. Then we have A b double of $b b'$, and A c double of $c c'$, and so on, and $a a'$, $b b'$, $c c'$, &c., will increase in exactly the same proportion as A a , A b , A c , &c.; so that if A $b = 2$ A a , then $b b' = 2$ $a a'$, and so on. Still $a a'$, $b b'$, &c. can never be taken equal to A a , A b , &c. We may, however, in this case make them equal by multiplying $a a'$, $b b'$, &c., by 2, which is the constant quantity here required, but which constant in the above formula we require to determine.

†To get the value of C, let the difference between the true and observed distance = x , then we have $d \pm x = \delta \times C$. Take now any two values of d , say in points E and G, as given in the former table; then we have

$$3.62 \pm x = 1 \times C \text{ for point E,}$$

and

$$4.62 \pm x = 1.414 \times C \text{ for point G.}$$

Subtracting equation of point E from equation for point G, we have

$$1.01 = .414 \times C, \text{ and } C = \frac{1.01}{.414} = .24 \text{ nearly.}$$

Upon a mean of the whole series of experiments for all the curves 1, 2, 3, 4, 5, M. Lambert finds the mean value of $C = 2.2$, or, as he expresses it, $\frac{11}{5}$.

The respective errors, therefore, or

$$d - \triangle \text{ are, } 2.71 - 1.58 = 1.13 \text{ for point } d,$$

and

$$4.61 - 3.11 = 1.5 \text{ for point } G.$$

The mean of these, or $\frac{1.13 + 1.5}{2} = 1.31$ nearly, which turns out to be

the mean value of x upon the whole series of experiments in the different curves, that is, the quantity to be subtracted from the measured distances in order to obtain the true distances, upon the hypothesis that the force is as the squares of the distances inversely, as in the case of gravity. These numbers x and C being determined, we have $d - 1.31 = \delta \times 2.2$, and hence $d = \delta \times 2.2 + 1.31$, which is the formula deduced by M. Lambert for determining d by calculation, and comparing the result with d , as given in the first table.

In extending this formula through the numbers for the series of curves 1, 2, 3, 4, 5, deduced as in the first table, M. Lambert finds the differences between the measured and calculated values of d comparatively small, and as often positive as negative; and hence concludes that the formula $d = \delta \times 2.2 + 1.31$ is, upon the whole, correct.

167. Admitting the truth of this formula, we arrive at a somewhat remarkable result, viz., that to obtain the distance, the square of which is in a reciprocal inverse ratio of the force of the magnet, we must take, for the true distance, the distance between the center of the needle and the extremity of the magnet, minus the quantity 1.31, which is greater than half the length of the needle.* So that what may be called the center of attraction of the magnet is found out of the magnet, and what may be called the center of attraction of the needle is found out of the needle. So that the common center of attraction may be conceived to be in the semi circular interval $A p$ (Fig. 94) being as much nearer the needle ($p q$) as its force is less than that of the magnet (E). M. Lambert thinks that, in the case before us, it falls about the point r , at 1.31 distance from the center of the needle, $C A$ being the least radius or distance at which the magnet could be placed without altogether fixing the needle independently of the polar force.

Professor Robison appears to view this deduction as somewhat anomalous, and as arising out of the complicated nature of the experiment. Yet if the force be such as anticipated by Lambert, there does not appear any greater difficulty in conceiving such a result than in conceiving the common center of gravity of two bodies of unequal magnitudes to fall without the bodies. Thus the common center of gravity of the earth and moon is neither within the earth or moon, but in some point intermediate between them; being as much nearer the earth as the mass of the earth is greater than that of the moon.

Under this impression, however, the professor was led to repeat Lambert's experiments with magnets, consisting of a slender steel rod, ter-

* The unit of measure being made=half the length of the needle.

minating in small balls, in which case he found the force to be nearly in the center of each ball, and to vary in the inverse duplicate ratio of the distances with singular precision.

168. Such are the principal features of Lambert's first memoir on the important question of the law of magnetic force. In a following subsequent memoir "On the Curvature of the Magnetic Current," he continues his series of experiments, and examines with singular ingenuity, mathematical skill, and address, the action of the directive or polar force of a magnet upon a small needle. In the preceding experiments, Lambert had always preserved the axis of the magnet in a right line passing through the center of the needle. This condition, however, is not altogether requisite in every case. He therefore, in these subsequent researches, places the magnet more or less oblique to that line, but always preserving the same angle of obliquity for comparative experiments. The question whether such curves as those which are represented (28) depend on a circulating fluid, Lambert considers of no moment. Still the curves exist, and the problem for determining the nature of such curves will still arise; the axis of a small needle freely suspended will, in various points, always be a tangent to these curves; so that we may, without ambiguity of language, call them "curves of the magnetic current." If there be such a current, the term will be true to the letter; if not, the algebraic nature of such curves will suffer no change. In order to determine the nature of these curves, as bearing on a large and important class of natural magnetic phenomena, Lambert endeavors to examine still further the general laws of magnetism, and the position, size, figure, and force of the great magnet which he supposes to reside in the earth. The limits of this work will not permit us to enter fully upon this beautiful memoir, which, as remarked by Dr. Robison, would have done credit to Newton himself; more especially as it embraces other considerations than those immediately connected with our present subject. So far, however, as it bears on the elementary laws of magnetism, Lambert concludes, "that the effect of each particle of the magnet on each particle of the needle, and reciprocally, is as the absolute force or magnetic intensity of the particles directly, and as the squares of the distances inversely."

169. About twenty years after Lambert's experiments, Coulomb turned the attention of his ingenious and comprehensive mind to this subject; and by means of the torsion balance, and method of oscillation, not only confirmed the deductions of Lambert, but also added to our knowledge of magnetic force in a most extraordinary degree. Having placed a linear magnet, 24 inches in length, in the stirrup of his balance, he was enabled to measure the force required to maintain this needle at various angles from its natural direction, and thus, by a direct experiment, he confirmed the principle of Lambert, viz, that the force urging a magnetic needle toward the magnetic meridian when drawn aside from it, is proportional to the sine of the angle of its deflection. Referring to

the explanations given, the following are the forces and angles in four different experiments, and by which it will be seen that the forces or degrees of torsion requisite to maintain the needle at the given angles are sensibly proportional to the sines of these angles:

Micromatic circles	1	2	4	5.5
Degrees of torsion	349.5	698.75	1394	1895
Angles of deflection	10°-30	21°-15	46°	85°
Sines of angles	.1822	.3324	.7193	.9961

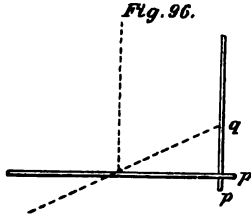
170. To understand clearly these results, it will be necessary to recollect that the reactive force exerted by the wire, when subjected to twist, is exactly proportional to the degree of twist to which it has been subjected. This is the fundamental principle of the instrument. This degree of twist or torsion may be either measured by actually twisting the wire itself at its upper extremity against a resisting force beneath, or otherwise turning the wire from below against a fixed point above. In either case the torsion force is proportional to the angle of torsion. Now, in such experiments as those just quoted, in which a magnetic needle is forced from its directive position through a given angle, say 46°, by actually twisting the wire any number of degrees against the directive force of the needle, and by which it tends to the magnetic meridian, we must, to obtain the actual force of torsion, holding the needle at any given angle, subtract from the number of degrees which we have twisted the wire, the degrees representing the angle of deflection of needle; for, imagine that we had forcibly retained the needle in its original position, whilst we had twisted the wire 4 circles of the micrometer, that is, 4 times 360°=1440°, and that, on liberating the needle, it became deflected, and rested at 46°, then, as is evident, the total torsion of the wire would become relaxed by that quantity, and we should have for the absolute force of torsion, holding the needle at 46°, 1440—46=1394°, as given in the table; and similarly for the other given angles.

171. Having determined this point, Coulomb proceeds to examine the law of the repulsive force of two similar magnetic poles, and in the following way:

Two equally-tempered and magnetic steel wires, each 24 inches in length, and about one-tenth of an inch in diameter, were placed, one of them in the balance, and the value of its directive power or force dragging it to the meridian at any given angle determined. This force, in terms of the torsion force, was, for this particular case, equal to 35° for 1° of deflection of the needle; that is to say, in order to force the needle 1° from its meridian, it was requisite to turn the micrometer 35° of the circle.* This being ascertained, the other wire was placed vertically in the meridian, with its inferior pole at right angles

* Coulomb found that two circles of torsion deflected the needle 20°, which gave a force of torsion for 20° = 720 — 20 = 700. Now the directive force of the needle being as the sine of the angle of deflection, we may, from this experiment, obtain the force for any other angle m , since we have this proportion, 700 or force at 20° : f , the

to the similar pole of the needle, as represented in the annexed Fig. 96, and in such way as to admit of the two wires



being considered as intersecting each other at an inch within their similar polar extremities $p p'$. As a necessary consequence, the pole p' of the horizontal needle, placed in the balance, becomes repelled, and turns away from the pole p of the fixed vertical needle, until arrested by the torsion of the wire, and a balance obtained to the repulsive force. In this case the needle was balanced at an angle of torsion of 24° . The next step was to determine what amount of torsion was requisite to balance the repulsive force at certain other angles or distances between the repelling poles $p p'$. With this view, the wire was twisted against the repulsive force by turning the micrometer 3 complete circles, or $3 \times 360^\circ = 1080^\circ$. The pole p' of the needle now stood within 17° of the vertical pole p . In like manner, 8 circles or $8 \times 360^\circ = 2880^\circ$, brought the repellent poles within 12° of each other. Let us pause here for a moment to consider what are the actual or total forces in operation at each of the arcs of distance 24° , 17° , and 12° .

172. In the first place, we have to consider, that not only is the horizontal needle p' pressed back toward the vertical needle p , by the reactive force of the torsion, but it is likewise urged toward the vertical needle by its own directive power or tendency to the meridian; we must therefore add this assistant force in each case. This is effected by turning it into degrees of torsion, at the rate of 35° of torsion for each degree of angular deflection from the meridian, according to the preliminary experiment above given; for, since as a fundamental principle of the instrument, the torsion force goes on regularly increasing with the angular twist of the wire, it is sufficient to know the actual force for 1° to get the force for any number of degrees. In the first experiment, therefore, when the angular distance of the poles $p p'$ was 24° , the total force in terms of torsion, balancing the repulsive force, must have been $24 + (24 \times 35) = 24 + 840 = 864$. For force at angular distance 17° , we have to combine the new torsion = 3 circles, with the torsion for 17° , and the directive force at 17° , so that we have $(3 \times 360) + 17 + (17 \times 35) = 1080 + 17 + 595 = 1692$ for the total force at angle 17° . In like manner, we obtain the total force at $12^\circ = 8$ circles + $(12 \times 35) = 2880 + 82 + 420 = 3312$; so that the distances and corresponding forces will stand thus:

Distances	12	17	24
Forces	3312	1692	864

force at angle m :: sin 20 :: sin m , or $f \times \sin 20 = 700 \times \sin m$, or $f = \frac{700 \times \sin m}{\sin 20}$. If we take the arcs themselves, instead of the sines, which we may do here without any great error, we have

$$f = \frac{700 m}{20} = 35 m.$$

If we take $m = 1^\circ$, then the force equals 35° , that is 35° of torsion, as observed.

173. Now these forces are in the inverse duplicate ratio of the distances, or very nearly. Thus, at distances 12 and 24, which are as 1 : 2, we have the inverse forces 864 and 3312, which are as 1 : 4; that is to say, we have the inverse proportion $3312 : 864 :: 2^2 : 1$, or $4 \times 864 = 3312$ nearly, or $3456 = 3312$. Had the force at 24° been 868 instead of 864, the accordance would have been complete. Now the difference 36 between these numbers is not above 1° of error in the position of the needle, at the rate of 35° of torsion to 1° of angular deflection; the result, therefore, is perhaps as near as could be expected, for it is to be remembered that the action of the poles upon each other is a little oblique; the distances are really as the chords of the arcs, and not as the arcs themselves; beside that, the experiment is not an experiment with two particles, but two portions of a magnetic wire. Admitting all this, however, it is still to be observed, that the force at the near distance 12 is not so great as it should be by calculation in the proportion of 3312 : 3456, taking the force at 24 as 864. We shall have occasion to refer to this fact as we proceed.

174. These experiments by Lambert and Coulomb were followed up, about the year 1817, by Professor Hanstein, of Christiania, who, in a valuable work entitled "Inquiries concerning the Magnetism of the Earth," deduces many important laws of ordinary magnetic forces.

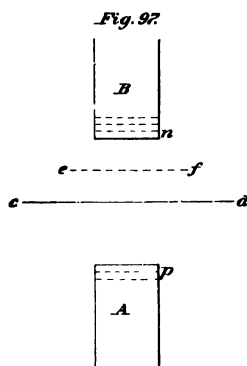
Although Professor Hanstein's method of experiment is virtually the same as that of Hawksbee, yet the method of analysis is peculiarly his own. Hanstein's apparatus may be taken as identical with that described in Fig. 79, the straight line E W being divided into portions such that ten of them were equal to the half axis of the artificial magnet used in the experiment. Having assumed that the magnetic intensity of any particle in a magnet is proportionate to some power of the distance from the magnetic center, and that the force between any two particles is in some inverse ratio of their mutual distance, a general expression is deduced for the effect which a linear magnet would have upon a magnetic particle situated anywhere in the line of the prolonged axis of the magnet. This determined, and the angles of deviation of the needle (Fig. 79), at different distances from the magnet (M), accurately noted for each distance, the professor proceeds to compare the results of calculation with those of the actual experiment, and shows that the supposition of the force being in an inverse power of the distance equal to 1 or 3, entirely disagrees with observation; whilst, on the other hand, if the power be made equal to 2, the numbers found by experiment differ but little from those found by calculation. The value of the power of the distance, representing the increase or decrease of intensity from the magnetic center, does not appear to have so great an influence on the result. Hanstein, however, thinks that this power is also equal to 2, although, by taking it as 1 or 3, the differences from actual observation are not always considerable.

From these inquiries, Hanstein thinks he is entitled to conclude.

"that the attractive or repulsive force with which two magnetic particles affect each other is always as their intensities directly, and as the square of their mutual distance inversely," thus confirming the deductions of Lambert and Coulomb.

175. Further inquiries concerning the nature and laws of magnetic forces.—Although our knowledge of magnetic force has been very greatly advanced by these several researches, it yet remains to be seen whether the law deduced be a general law, applicable to every case of magnetic action considered as a central force, or whether it be only a particular law of some peculiar agency operating between the surfaces of magnetic bodies in a way similar to that of electricity, which, as now well known, is confined to the limiting surfaces of opposed conductors.

We have seen that when a magnetic bar A (Fig. 97) is opposed to a



similar, but smaller, bar of iron B, then a new polarity (n) is induced in the near parts n of the iron, opposite in kind to that of the opposed polarity A, whilst another polarity (q) arises in its more distant parts, similar in polarity to that of the polarity A, but opposite to that of the induced polarity n ; this, however, is not all. On further examination, we find that the temporary polarity n , thus induced in the near surface of the iron, operates in its turn on the near surface p of the magnet, producing there, by a species of reflection or reverberation, what may be considered as

a new polarity p , opposite in kind to that of the induced polarity n , but similar to that of the permanent polarity A; that is to say, a portion of the force, which, under the ordinary conditions of magnetized steel, is directed towards the center of the magnet, becomes now determined toward the iron in direction $p\ n$.

¶ These changes, induced in the magnetism of the two bodies, have been considered by some writers as casual and disturbing forces, super-added, as it were, to the primary magnetic action, which they imagine to be a distinct power, or emanation, as it were, from a center, and operating in the way of other central forces. Michell had evidently adopted this view; as also Dr. Robison, who thinks that the phenomena of magnetic attraction and repulsion, as commonly observed, are not calculated to develop the real law of magnetic force: "For in the experiments made on attraction at different distances, the magnetism is continually increasing, and hence the attraction will appear to increase in a higher rate than the just one;" and that, hence, "the observed law must be different from the real law." If we look, however, very narrowly into the nature of this kind of physical force, we shall immediately perceive that it is altogether an inductive process. Induction, as observed by Faraday, in respect of electricity, is the essential function of all magnetic development. So far, therefore, from

these induced actions being merely superadded or disturbing forces they are the very essence of the force itself. It is, in fact, the mutual play of these inductive powers which constitutes magnetic action in all its variety of form; we recognize no other action in the observed phenomena of magnetic attractions and repulsions; and it is hence to the laws of these induced changes to which we must look for an intelligible development of what we have termed the general law of magnetic force.

176. It is here to be remembered that we know nothing of that peculiar condition of steel we term magnetic, except through the medium of its effects upon ferruginous bodies. We may, however, infer, as already explained, that in a magnetized bar two forces are developed, the tendency of which is to recombine and restore the condition of neutrality under which they previously existed. Taking, therefore, a magnetic bar apart from the influence of all other ferruginous matter, we may consider the action of these opposite forces as being directly upon or toward each other, either through the particles of the steel or through surrounding space. The experiment we have adduced, Fig. 15, is highly illustrative of this kind of action; the ferruginous particles being evidently bent into curves, and apparently uniting the forces in points similarly placed on each side of the magnetic center. When, therefore we present to one extremity (p , Fig. 97) of a magnet A , a mass of iron B , capable of assuming the magnetic state or otherwise, the opposite pole of another magnet, we divert, as it were, some portion of the force resident in that extremity p from its previous direction towards the center of the bar A , and cause it to act in the direction of the opposed iron or other opposed polarity. And this it is which constitutes the reciprocal or reflected force p (Fig. 97), to which we have just adverted, and it is upon these two forces that the reciprocal force between the two bodies depends.

177. This species of reverberation of force between the opposed poles, having once commenced, may still continue; that is to say, a secondary wave or reverberation may proceed from the new force p , which, reaching the iron, is again reflected back upon the magnetic pole, calling into activity a still further portion of the opposite force in the direction of the iron; each reverberation becoming weaker until the wave vanishes, as it were, into rest.

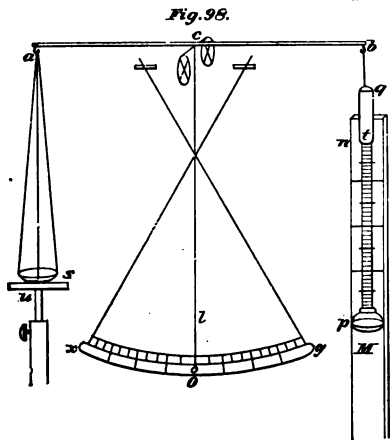
The late Mr. Murphy, of Caius College, Cambridge, applies, in his profound mathematical work on "Electricity and Heat," a somewhat similar principle to the theory of electrical action, and which he terms "Principle of Successive Influences." Prof. W. Thomson also, of the Glasgow University, resorts to a view of this kind, conceiving that in the reciprocal force of attraction, as exerted between a charged and neutral body, certain images or reflections of power are produced within the opposed conductors, and which become perpetuated in a way similar to that of reflections between two mirrors.

How, or in what way, the kind of influence to which we have just

adverted commences, or whence it first proceeds, has never yet been fully explained. The first action may, for anything we know to the contrary, proceed from the influence of the iron on the magnet; the magnet being a body in a peculiar condition, which renders it sensible of impressions from ferruginous matter. Hence may arise that determination of a given portion of the polarity next the iron which we have just described, and upon which may depend a subsequent and similar determination of the opposite polarity resident in the iron toward the magnet, and a retiring, as it were, of the similar polarity in the reverse direction. In whatever way, however, these two inductions arise, they are evidently the immediate source of the reciprocal attraction as observed to arise between the opposed bodies: this appears in great measure evident in Fig. 16. On the contrary, when these inductive actions do not arise, or if they be resisted by any existing magnetic condition, then not only is there an absence of all apparent force, as we perceive in presenting to the pole of a magnet any non-magnetic body, but a totally opposite force ensues: the bodies actually repulse each other; as also fully indicated in Fig. 17. Moreover, it may be shown that the attractive force between a magnetic pole and soft iron is only in proportion to the induction of which the iron is susceptible, whatever the amount of permanent magnetic development in the steel.

Magnetic attractions and repulsions, then, as commonly observed, being the result of a species of inductive reverberation between opposed magnetic bodies, it follows that, in order to arrive at a correct view of this species of force, and determine the law of its action, we must necessarily commence with an investigation of the laws and operation of the elementary forces of induction.

178. The magnetometer already described, Fig. 71, and the simple balance-beam adverted to, Fig. 28, are well adapted to the measurement



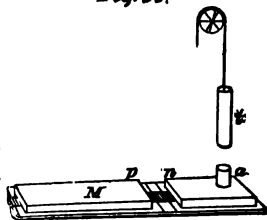
of these and other magnetic forces. The first has been very fully explained in all its details; the latter, when applied to very refined purposes, should be mounted on friction-rollers, such as shown, Fig. 70. and the whole of the frame-work, with its attached arc, be sustained on a central sliding column of support, the altitude of which can be varied by means of rack-work, as in the column of the magnetometer, Fig. 71, so as to change the distance readily between the small trial cylinder *t* (Fig. 98), or other body suspended from one of the arms, and any other magnetic substance *M* brought to act on it. The general arrangement is represented in the annexed fig-

ure, the frame-work and column of support being omitted in order to avoid complication. In the instrument as here shown, the suspended bodies play freely on two pins run transversely at a and b through slits cut in the extremities of the beam, which is 16 inches long. The scale-pan s is supported on a small circular plane, set on a sliding piece, u , so as to admit of adjustment. The arc xoy is the one-eighth part of a circle, and is divided into 100 parts on each side the center o , which is marked zero; the radius of the arc is 16 inches, the index l is neatly formed of three or four pieces of reed straw, terminating in a fine bristle; it is attached to the balance at c by insertion on a brass pin projecting from a light brass band encircling the beam, and through which the axis passes. The forces corresponding to any given number of degrees of the arc are determined experimentally by placing small weights, either in the scale-pan at s , or on the suspended iron t . The axis being a little above the center of gravity of the beam, the balance does not immediately overset, but admits of a given inclination; the forces in this case will be very nearly as the small angles at which the beam inclines; so that the degrees of the arc measuring these angles will be nearly as the weights inclining the beam. Attractive forces are measured on the arc in the direction ox , repulsive forces in the opposite direction oy .

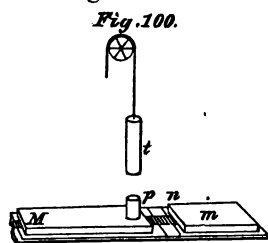
This balance is only applicable to the measurement of very small forces, *such as those exerted by magnets and iron at distances approaching the limit of action*. In the application of it, we employ precisely the same kind of apparatus for sustaining the magnets and iron as that already described for the hydrostatic balance.

179. The direct and reciprocal forces of induction are examined by these instruments according to the methods described. To determine the law of the direct induction, the magnet and iron are attached to a divided scale (Fig. 74), and then brought under the trial cylinder; so that in making the distance ab constant, and varying the distance NS , the rate of increase or decrease of the induction upon the near extremity S of the intermediate iron, as measured by the distant and associated polarity at b , may be pretty fairly estimated; the reciprocal attraction between the trial cylinder t and the induced pole b will, as observed by Newton, entirely result from the intermediate iron; hence we may infer. all other things being the same, that the proximate induction at S will vary with the distant polarity at b . When the bodies are laid horizontally, as in the annexed Fig. 99, the trial cylinder t is immediately over the distant extremity of the iron, the force being taken through a short cylindrical armature, a . Fig. 74 is further illustrative of this experiment. To measure the reflected force, we first observe the degrees of attraction between the pole

Fig. 99.



of a magnet and the trial cylinder t , placed as in Fig. 99, or as in Fig. 100.



A mass of iron, m , or the opposite pole of a permanent magnet, is then caused to approach the pole p of the magnet M , through certain measured distances, as before; this will cause the index to decline. Now the degrees of declination may, within certain limits, be taken as a measure of the reciprocal force of the induced pole n upon the pole p of the magnet M , the distance of the trial cylinder t being constant, and the force allowed to operate through a short cylindrical armature of soft iron, as before.

The forces of induction may in all these cases be considered as proportional to the square roots of the degrees of attraction, as given by the instrument, since by a law of charge which has been fully established in similar electrical actions, and which we shall further show as equally true for magnetic actions, the force is as the square of the quantity of magnetism in operation.

180. It appears, by an extensive series of experiments conducted in this way, that a limit exists in respect of these elementary inductive forces, different for different magnets, and varying with the magnetic conditions of the experiment, toward which the increments in the force continually approach with greater or less rapidity, as the distance $p\ n$ (Fig. 97) is diminished, as if the opposed bodies were only susceptible of a given amount of magnetic change.

Taking the force toward the limit of the action, the amount of induction is in some inverse ratio greater than that of the simple distance; it was not found, however, in any case which could be satisfactorily determined, to exceed the inverse sesquiplicate ratio, or $\frac{3}{2}$ power of the distance. As the distance becomes diminished, the induction approaches the inverse simple ratio of the distance and varies commonly according to that law. At less distances, the induction begins to vary in some ratio less than that of the simple distance inversely, such, for example, as the $\frac{2}{3}$ power of the distance inversely. At small distances the induction was generally observed to be as the $\frac{1}{2}$ power, or square roots, of the distances inversely; thus causing corresponding changes in the general law of attraction reciprocally exerted between the opposed bodies.

When the convergence is slow, the law of the induced forces may be taken for a long series of terms as constant; but should any circumstance interfere to accelerate the convergence, such as a particular texture or condition of the magnetic steel or iron, or a high magnetic power, then the law of force may appear subject to irregularity. As a general result, however, we may conclude that the elementary force of magnetic induction is as the magnetism directly, and from the $\frac{1}{2}$ to the $\frac{3}{2}$ power of the distance inversely.

181. This understood, let us see how far these results may be applied in explanation of the different laws of force experimentally deduced by

the many eminent philosophers who have turned their attention to this important question.

Let A, Fig. 97, represent a magnet opposed to a similar mass of iron, B, at some given distance, $p\ n$. Let the small space n be taken to represent the direct induction on the near extremity of the iron B, and the small space p the reciprocal or reflected induction on the near pole of the magnet A; and suppose that every magnetic particle in n attracts every magnetic particle in p , and reciprocally. Moreover, let all the particles in $n=a$, and all the particles in $p=b$, and take distance $p\ n$ as a unit of distance; then, total force at this distance=1 will be represented by $a \times b=a\ b$. For the attraction of one particle of n to all the particles in p will be as b , the attraction of two particles of n to all the particles of p will be as $2\ b$, of three particles as $3\ b$, of m particles as $m\ b$, so that if b represent all the particles, and $m=a$, the total force will be $=a\ b$.

Suppose, now, we decrease the distance. Let the distance, for example, be reduced to one half $p\ n$, the magnet A being brought up to the line $c\ d$; then, supposing the induction to vary as the simple distance inversely, n will become $2\ n$, and p will become $2\ p$. In this case call the particles in $n=2\ a$, and the particles in $p=2\ b$; then, considering $2\ a$ and $2\ b$ as double particles, we have attraction of one double particle in n for all the double particles in p , as $2\ b$; of two double particles in n , for all the double particles in p , as $2 \times 2\ b=4\ b$; of three double particles as $3 \times 3\ b=9\ b$; and so on to m particles, which will be as $m \times 2\ b=2\ m\ b$. If $m=2\ a$, the total force will be represented by $2\ a \times 2\ b=4\ a\ b=2^2\ a\ b$.

Let distance $p\ n$ be now further reduced. Suppose it reduced to $\frac{1}{3} p\ n$, and that the magnet be now brought up to the line $e\ f$. Then, according to the same law of induction, n becomes $3\ n$, and reflected force p becomes $3\ p$. Reasoning as before, we have total force $=3\ a \times 3\ b=9\ a\ b=3^2\ a\ b$. If distance be now diminished to $\frac{1}{4} p\ n$, we have similarly total force represented by $4\ a \times 4\ b=16\ a\ b=4^2\ a\ b$; and so on.

Taking, therefore, first force $a\ b$ as a unit of force, and distance $p\ n$ as a unit of distance, we have, at distances $1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}$, &c., the corresponding forces $1, 2^2, 3^2, 4^2$, &c.; that is to say, the forces are in the inverse duplicate ratio of the distances, according to the law of Lambert and Coulomb.

EXPERIMENT 50. This law may be verified experimentally by placing a magnet, Fig. 98, immediately under the trial cylinder t , and taking the forces within a range of about one-third to two-thirds of the sensible limit of action. Thus the forces and distances, as deduced by the hydrostatic magnetometer, were as follow; the distances being taken in tenths of an inch, the forces in degrees:

Distances	12	10	8	6	5
Forces	2	3	5	8.5	12

182. We will now take a case in which the induced forces, in approaching a limit, are no longer in the inverse ratio of the simple distances,

but as the $\frac{1}{2}$ power, or square roots, of the distances inversely. Then, taking a unit of force $= a b$, and the unit of distance $= p n$, and reasoning as before, suppose in decreasing the distance to line $c d$, that is, to one-half the former distance, induced force n , instead of becoming $2 n$, is now only $1.4 n$, or nearly, whilst p , instead of becoming $2 p$, is now only $1.4 p$, that is, the square roots of the distances inversely. In this case, calling force at distance unity $= a b$, we have force at distance $\frac{1}{2} = 1.4 a \times 1.4 b = 2 a b$ nearly. Similarly, in decreasing the distance to $\frac{1}{3} p n$, n becomes $1.73 n$, instead of $3 n$, and p becomes $1.73 p$, instead of $3 p$, and we have for total force at distance $\frac{1}{3} = 1.73 a \times 1.73 b = 3 a b$; and so on. Thus, whilst the distances are $1, \frac{1}{2}, \frac{1}{3}$, &c., the forces are $1, 2, 3$. In this case, the reciprocal forces of attraction are as the distances inversely, according to the law observed by Muschenbroek, cases 1 and 2; Cëpinus also arrived at a similar result.

EXPERIMENT 51. This law may be fully verified by experiment, as in the preceding case, by taking the force and distances within about one-third the sensible limit of action. Thus, with a given magnetic power, the distances being 4 and 2, the forces were 8 and 16. In comparing the distances and forces with magnets of low power, especially in cases of magnets by induction, the forces are generally as the distances inversely. Let, for example, the distance $S N$, Fig. 74, be made constant, and distance $a b$ varied, the reciprocal forces of attraction between a and b will be almost invariably as the distances inversely.

183. Should the induced forces in any case vary in some other inverse ratio of the distance—suppose, for example, it should approach the $\frac{2}{3}$ power of the distance, which it may—then, on diminishing distance to the line $c d$ (Fig. 97) $= \frac{1}{2}$ distance $p n$, force n will become $1.68 n$ instead of $2 n$, and force p will be $1.68 p$ instead of $2 p$, and we should have the total force at distance $\frac{1}{2}$ expressed by $1.68 a \times 1.68 b = 2.8 a b$ nearly. Similarly at distance $\frac{1}{3}$ it would be $2.8 a \times 2.8 b = 7.84 a b$; since, according to the same law, n would become $2.8 n$, and p would become $2.8 p$, instead of $3 n$ and $3 p$ (180), and so on. In this case, whilst the distances are $1, \frac{1}{2}, \frac{1}{3}$, the forces are $1, 2.8, 7.8$; that is to say, they are in the inverse sesquiplicate ratio, or $\frac{2}{3}$ power, of the distances, according to the law deduced by Martin in three very unexceptional experiments; that is to say, at $\frac{1}{2}$ and $\frac{1}{3}$ the distance the forces become nearly 3 times and 5 times as great.

EXPERIMENT 52. This result may be verified, as in the preceding experiments, by noting the distances and forces within about $\frac{1}{3}$ and $\frac{2}{3}$ of the sensible limit of action. Thus, at distances 8 and 4, the forces were 5 and 14, being in the inverse sesquiplicate ratio of the distance, or very nearly.

184. When the induced forces vary in any inverse ratio greater than that of the simple distance, we obtain laws of force in an inverse ratio greater than that of the second powers. Let, for example, the induced forces approach the $\frac{2}{5}$ powers of the distances inversely, so that on re-

ducing distance $p n$ to $\frac{1}{2} n$, n becomes $2.83 n$; at distance $\frac{1}{3}$ it becomes $5.2 n$, and so on; instead of $2 n$ and $3 n$, as in the first case. And let force p vary similarly; then we have force at distance $\frac{1}{2} = 2.83 a \times 2.83 b = 8 a b = 2^3 a b$; at distance $\frac{1}{3}$ it would be $5.2 a \times 5.2 b = 27 a b = 3^3 a b$, and so on; that is to say, taking $a b$ as a unit of force at a unit of distance $= p n$, as before, we have at distances $1, \frac{1}{2}, \frac{1}{3}$, the corresponding forces $1, 2^3, 3^3$, &c., that is $1, 8, 27$; by which we perceive that, as the distances decrease, the forces increase in the proportion of the cubes of the distances inversely; being the law of force given by Sir Isaac Newton.

EXPERIMENT 53. We may verify this result experimentally by taking the forces and distances from about $\frac{2}{3}$ to $\frac{5}{6}$ of the limit of action. The balanced beam (Fig. 71) is well adapted to this experiment; and if we substitute a small magnet for the trial cylinder t , so as to extend the limit of action, then this law will become very apparent. Thus, at a distance of 6 inches, the force was observed to be 2° ; at 3 inches it increased to 16° .

185. By taking the induced forces $p n$ in some other inverse ratio, we may in a similar way obtain a law of force such as found by Brook Taylor, Whiston, and Hawksbee. Suppose, for example, that at distance $\frac{1}{2}$, n becomes 2.37 times as great, and that p varies with it, we should then have the total force at distance $\frac{1}{2} = 2.37 a \times 2.37 b = 5.6 a b$ nearly, which would be as the square root of the fifth power of the distance inversely, and which result may frequently be obtained in taking the forces and distances within limits from about the $\frac{2}{3}$ to $\frac{3}{5}$ of the sensible distance of action.

If magnetic forces could be satisfactorily traced to the limits of their vanishing points, we might probably obtain laws of force in the inverse ratio of the fourth or fifth powers of the distances; at least there appears no reason to suppose that the law of the inverse cube of the distance is the ultimate law of this species of the force, supposing it to depend on the mutual play of the inductive actions we have described.

186. It may be, perhaps, as well to remark here, that in all these laws of force as thus deduced, and which differ from that of the inverse square of the distance, the same result may be arrived at in supposing a limit to one only of the forces. If we suppose, for example, the reflected force p (Fig. 97) to change so little at small distances from the magnet as to admit of being taken as constant, then the total force would vary with the other; that is to say, it would be as the distance inversely, supposing the direct force to continue according to that law. Thus, suppose at distance $\frac{1}{2}$, force n became $2 n$, whilst force p remained unchanged, we should then, calling force at a unit of distance $a \times b$, as before, have the force at distance $\frac{1}{2} = 2 a \times b = 2 a b$; that is to say, the distances being as $2 : 1$, the force would be as $1 : 2$. A similar reasoning applies to all the other cases. It is, however, more in accordance with observation to suppose the two forces to vary together.

187. The reciprocal attraction between the opposite poles of two magnets differs only from that of the force exerted between a magnet and iron in degree of distant action, not in kind. By the presence of permanent polarities in both the opposed surfaces, instead of in one only, the inductions upon which the subsequent attraction depends are greatly facilitated. In the force as exerted between a magnetic pole and mere iron, the pole n (Fig. 97), upon which the reflected force depends, has first to be produced; that is to say, the magnetic forces resident in the iron must be first developed, and a portion of one of them determined in the direction of the magnet; whereas, in the reciprocal force between opposite magnetic poles, this portion of the attractive process is already complete, and the remaining part is a determination of the opposite forces in each bar in the direction of the opposed poles. In this case, the limit of the distance at which the forces act is very considerably increased; by employing a small and powerful trial magnet in the balanced beam (Fig. 98), we may obtain indications of measurable force at a distance of 10 inches or more; with delicately suspended needles and large magnets Scoresby obtained indications of force at distances of 50 or 60 feet.

188. If we proceed to investigate the laws of magnetic repulsion, as exerted between similar magnetic poles, we shall find the same mutual play of reciprocal inductive force as in the case of attraction, with the exception that the tendency of the inductions is in a contrary direction to that of the existing magnetic developments (Fig. 17), and consequently to subvert the opposed poles. Now, the resistance to this subversion by the already-established polarities is probably the source of the repulsive effect. In conformity with this result, if we present to the pole of the magnet M (Fig. 100), whilst acting on the trial cylinder t , the similar pole of a second magnet, m , the force on the trial cylinder will appear to increase. This is, in fact, the converse of the result already adverted to. Here the tendency of the induction is to repulse the similar polarity, and so increase its operations in other directions; we could hence deduce the law of this induction by observing the increase or decrease of the force upon the suspended cylinder, as the distance between the two magnetic poles is varied.

Supposing the laws of the inductive force to be the same as before, let the similar poles of two magnets A B (Fig. 97) be opposed to each other, and let the small space n be taken to represent the amount of the subversive tendency on the magnet B , and the small space p that on the magnet A ; then, calling all the active magnetic particles in $n=a$, and all those in $p=b$, and taking some distance p as a unit of distance, we have, according to a similar notation and reasoning before given, force at distance unity $=a \times b$; supposing the induction to vary as the distance inversely, and the polarity to remain unchanged, it will be at distance $\frac{1}{2}$ $=2 \ a \times 2 \ b=2^2 \ a \ b=4 \ a \ b$; at distance $\frac{1}{3}$ it will be $=3 \ a \times 3 \ b=3^2 \ a \ b=9 \ a \ b$, and so on, according to the law determined by Coulomb;

that is to say, the resulting force will be as the second powers of the distances inversely, and which may be verified experimentally by means of the two magnetic instruments employed in all the preceding experiments, similar instead of dissimilar magnetic poles being opposed to each other, and a limit of distance being taken, such as does not affect the existing and established polarities. If in this, as in the former case of attraction, we suppose the inductive action to vary, then we may obtain laws of force according to other inverse powers of the distance. In fact, we may suppose the induction to be such as will give any law of force consistent with the nature of magnetic action. It is not, however, probable, from the peculiar character of magnetic repulsion, that any law of force in a greater inverse ratio than that of the second power of the distance would be likely to obtain, although the force may be frequently found to vary, as is commonly the case in a less ratio; as, for example, in the inverse ratio of the simple distance, a very common law of repulsive force at comparatively small distances.

189. We have further to observe that, from the circumstance of the total repulsive power being dependent on the permanency of the opposed polarities, and on their relative intensity, we may infer that, in the case of opposed polarities of very unequal force, the weaker may, at some limit of distance, yield to the inductive action of the stronger, and so an opposite, but weak, polarity may become induced upon the subversion of the polarity before existing. In this case, the increments in the repulsive force would continue to decline, and the repulsion would at length be superseded by a weak attraction. This result is especially seen in Muschenbroek's experiments before quoted, and is easily obtained by means of the hydrostatic magnetometer, with magnets of very unequal force. Indeed, it is no uncommon case to find two magnets repel at some distances, and attract at others. Even if we employ two magnets of precisely equal power, the tendency is always to a mutual reversion of their poles; and this tendency is so powerful, as the distance between them becomes considerably diminished, that in no case do they remain unchanged. Under such conditions, therefore, experiments with repelling poles of opposed magnets would be open to considerable disturbance, and the results, as observed by Muschenbroek, not conformable to any regular law of force.

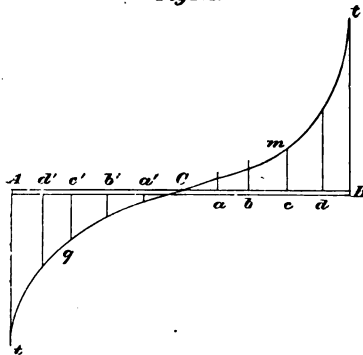
190. On a careful review, then, of these investigations, we find a fair solution of the seeming contradictions and differences in the results of experiments on the law of magnetic force by many eminent philosophers alike distinguished for their scientific learning and experimental ingenuity; and they appear to verify, in a remarkably clear and satisfactory manner, the truth of the deduction arrived at by the celebrated Brook Taylor, viz, "that magnetic attraction, as commonly observed, is quicker at greater distances than at small ones, and different for different magnets"; which, taking the facts as they present themselves in the

ordinary way, is undoubtedly the case, and is, if the principles we have laid down be exact, not merely an experimental fact, but a necessary result of the elementary laws of magnetism.

It is, perhaps, to be regretted, that from a predisposition to identify the law of magnetic attraction with that of central forces generally, several profound writers have been led to question the accuracy of every result opposed to such a deduction. Thus, it has been said of Newton, who found the force of magnetism nearly as the cubes of the distances inversely, that he had very inaccurate ideas of magnetic phenomena. It would be very difficult, however, to show from the little which this great author has advanced on this subject in his immortal work, the "*Principia*," in what his notions were defective; on the contrary, they appear to be in most perfect accordance with experiment, and true to the letter. In associating magnetic action with a law of the centrifugal forces of particles terminating in particles next them, Newton never pretended to offer any theory of magnetism, but says, with his usual diffidence, "whether elastic fluids do really consist of particles so repelling each other is a physical question," which he leaves philosophers to determine. On the other hand, the learned Dr. Robison is led to question the accuracy of all the results produced by Hawksbee, Brook Taylor, Muschenbroek, and others, conceiving them to have been defective and injudicious; and further states, as we have already observed, that magnetic attractions and repulsions are not the "proper phenomena for declaring the precise law of variation." Yet it was by the means of these very same attractions and repulsions that Lambert, and more especially Coulomb, deduced what this accomplished author considers to be the true law of magnetism.

191. *The law of force in different points of a magnetic bar.*—We have seen that the polar forces in a magnetic bar decrease rapidly as we recede from the extremities, and at last vanish in a point termed the magnetic center. If, therefore, we erect, between the magnetic center and pole (Fig. 101), a series of perpendiculars or ordinates $a b c$, &c.,

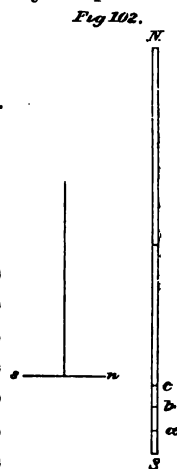
Fig 101.



such as may represent the force in given points, then it is certain these lines will increase rapidly as we approach the poles A B, and we should, in passing a line through the extremities of these perpendiculars, obtain for the force of the north and south polarities some such curve as that represented in the figure by the lines $C m t$, $C q t$, the ordinates being nothing in the center C. Coulomb endeavored to determine the value of these ordinates

in the following way:

Having determined the times of oscillation of a delicately suspended needle (*s n*, Fig. 102), a long magnetic wire (S N) was then placed vertically in the line of the magnetic meridian, immediately opposite the needle, the dissimilar polarities being opposed to each other. This would not of course change the direction of the needle; it would only affect the rate of vibration. The needle was now caused to vibrate opposite various points *S a b, &c.*, of this linear magnet, and at a constant distance from it. Then, taking the forces as proportionate to the square of the number of vibrations, and deducting the constant force previously determined, and by which the needle vibrates when the magnet S N is away, we obtain the force due to any given point *a b, &c.* In this experiment Coulomb supposes that the resulting force, as thus determined, is very nearly that of the point opposite which the needle vibrates; for, if we suppose the oblique forces of other points *a c*, on each side of a given point *b*, to influence the result, still one-half the sum of the equidistant oblique actions will not be very different from that of the given point *b*; for if the points on one side, *a*, are more powerful, those on the other are more weak; and whatever be the nature of the curve *C m t* (Fig. 101), which joins the ordinates, we may consider any very small portion (*m*) as a straight line. When, however, we come to the extremity of the wire or pole S, then, because there is no point outside it, as in the other cases, he doubles the number representing the square of the number of oscillations, by which artifice he renders the experiment for points near the pole comparable with the others. The curve of intensity thus traced by Coulomb is a species of curve termed the logarithmic curve, the ordinates of which (*a b c, &c.*, Fig. 101) are in geometrical progression, whilst the abscissæ *C a, C b, &c.*, corresponding to these ordinates, are in arithmetical progression.* M. Biot, who treats this question from Coulomb's manuscripts, concludes that this result is a necessary consequence of the law of magnetic force being as the squares of the distances inversely, and that magnetism, like electricity, is little sensible in a body of regular figure before we approach its extremities, when it increases very rapidly.



192. The results and progress of Coulomb's investigation are, it must be admitted, neither so perfect nor so satisfactory as could be desired, owing probably to the many difficulties which embarrass the experiment, and the uncertain condition of the line of particles of the steel as to temper and other circumstances. It is, therefore, doubtful whether the logarithmic curve really represents the law of intensity from the middle

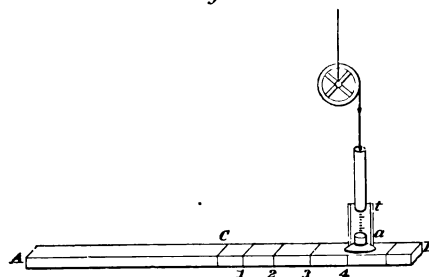
* That is to say, the abscissæ or distances *C a, C b, C c, &c.*, increase by the constant addition of some given number 1 2 3, &c., as the case may be, and the corresponding perpendiculars or ordinates *a b c d, &c.*, by a continued multiplication by some given number 2 3 4, &c.

point of the axis toward both poles. Lambert considers the force of each transverse element to be directly as the distance from the center, whilst Robison, who repeated Lambert's experiments, imagines that this is only true for certain magnets. The results of Hanstein's inquiries, before quoted, go to prove that the power of the distance representing the increase or decrease of the magnetic intensity between the center and the poles of a magnet agrees most perfectly when that power is taken = 2, or that the intensity of any magnetic particle situated in the axis is proportional to the square of its distance from the middle point of that axis.

193. Much uncertainty appears to have attended these inquiries, in consequence of a want of due attention to the regularity and temper, and the regular development, probably, of the magnetism throughout the bar. *It is well known that bars not regularly and equably tempered, or only hardened about the extremities, will not retain any magnetic power except in the tempered parts.* In other cases of very long bars, to which an adequate power for their complete magnetizing has not been applied, we have what has been called by Van Swinden culminating points; that is to say, they appear to consist of a series of magnets with opposite poles in contact. Added to this, the investigation has been further embarrassed by the methods of experiment; these have been more or less indirect and liable to uncertainty. We may, however, by a careful and skillful experimental arrangement, arrive at a fair approximation to the law in question, and in the following way:

EXPERIMENT 54.—Let a steel bar (A B, Fig. 103), of uniform texture, about 20 inches long, 1 inch wide, and three-tenths of an inch thick,

Fig. 103.



be very carefully and equably tempered throughout its entire length, and rendered powerfully magnetic by the usual process, and in such way as to bring the magnetic center C as nearly as possible in the center of the bar.

Verify the position of this center on the upper surface A B, by the process described (28), Experiment 12, and divide that surface on each side the center C into a given number of equal parts by lines 1, 2, 3, 4, &c., continued down over one side of the bar. These divisions may be about an inch and a half apart. The bar being thus prepared, place it edgewise on the table of support represented, Fig. 72, under the trial cylinder *t*, the divided surface A B being uppermost. Examine the forces at successive points (1, 2, 3, &c.) through a small cylindrical armature of soft iron (*a*), of the same diameter above as the trial cylinder (*t*), and about three-fourths of an inch or more in height, and at a constant distance (*a* *t*), this armature being fairly applied to the surface, and so as to cover a small space on each

side of any given division. The square root of the force thus taken in degrees on the graduated arc of the instrument (109) will very nearly represent the comparative magnetic development. We may, in fact, observe that by means of the armature *a* we place the trial cylinder sufficiently beyond the influence of other parts of the bar, whilst the action becomes reduced to two points, *a t*, or nearly so. Then, with respect to the armature itself, we may further observe that, supposing the resulting force to be partly derived from the oblique forces on each side of it, still those forces would be very inconsiderable as compared with that of the point actually covered by the armature. Besides, as remarked by Coulomb, if we conceive the points on the side next the center to be less forcible than those next the pole, still half the sum of all the equidistant forces would come very near the force of the point immediately under the armature, at least for a long series of points extending from the center *C*, but not carried quite up to the extremity of the bar. We may, therefore, obtain in this way such an approximation as will leave no doubt as to the law we seek to discover.

The experiment thus carried out gave the following results, the distance *a t* being three-tenths of an inch :

Distance from center	1	2	3	4	5
Force in degrees	1	4	10	17	28
Magnetic development or square root of forces ...	1	2	3.1	4.12	5.29

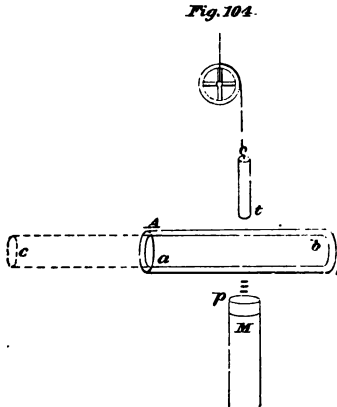
It appears, therefore, by these results, that the magnetism in different points of a regularly tempered and magnetized steel bar, of uniform texture, is directly as the distance from the magnetic center; whilst the reciprocal force between any given point and soft iron is as the square of the distance from that center. The distinction is important as regards all the preceding investigations, which may be taken to refer exclusively to what may be termed the intensity.

194. Laws of magnetic charge.—Magnetism, like electricity, appears to be a species of force confined to the surfaces of certain bodies without any relation to their mass. Its accumulation, however, or rather development, in tempered steel, rather partakes of the form of electrical excitation than that of accumulation on insulated conductors; when developed in soft iron by influence, the development is very analogous in character to that of electrical induction by the influence of charged upon neutral conductors. Now, although the terms magnetic charge, quantity of magnetism, and such like, may appear to convey a very hypothetical meaning, they are yet, if taken in the ordinary acceptance of such terms, as applicable to magnetic as to electrical action, since there must necessarily be some element of magnetism corresponding to the general term quantity, as expressive of the relative or absolute amount of the agency in operation, and upon which the observed phenomena depend. We have not, however, hitherto arrived at quantitative measures in magnetism, which, like the unit measure in electricity, determines the quantity of charge conveyed to coated glass.

We know not, in fact, by the ordinary process of magnetizing, what the relative quantities of magnetism may be, as developed in various bars; hence the investigation of such measures is of no small importance to the progress of magnetic inquiry.

By magnetic charge, then, we are to understand the amount or quantity of magnetism existing in a bar of tempered steel or iron, under a given attractive force, and which we may, as in electricity, term intensity. The following experiment shows that this intensity is independent of the mass of a magnetized body; and that consequently the magnetic development is entirely confined to the surface.

EXPERIMENT 55.—Let A B (Fig. 104) be a small cylinder of soft iron



about 2 inches long, one-half an inch in diameter, and one-tenth of an inch thick. Let *a b* be an interior solid cylinder, also of soft iron, closely applied to the interior surface of the external cylinder A B, but capable of being drawn out to any point *c*, or otherwise removed altogether. Let now this joint cylindrical mass be attached to a divided scale, and a magnet M, fixed at a constant distance *p* immediately under it, bring the whole immediately under the trial cylinder *t*, as represented in the figure, and according to the

arrangement more fully shown, Fig. 72. We may then estimate by the attractive forces on the trial cylinder *t* any change of intensity in the induced magnetism, the cylinder A B being taken either hollow or solid, or influenced by a greater or less extent of surface *c* A B. Things being thus arranged, and the distances *p* and *t* being regulated to within three-tenths of an inch, the following results were obtained: the force, as observed, with the joint cylinders A B and *a b* taken together as a mass, amounted to 10° ; under this attractive force, the interior cylinder *a b* being extended toward *c*, the intensity or force on *t* = 10° gradually declined; when the surface extended to the greatest limit *c*, the intensity was only one-half as great, the force then being only 5° . On removing the interior cylinder *a b* altogether, the intensity again returned to 10° , being precisely the same as at first. We may hence conclude that magnetism, like electricity, is influenced only by surface, and is altogether independent of the mass: a deduction further supported by the fact that a hollow tempered steel cylinder acquires as great magnetic power by the ordinary process of magnetizing as a solid tempered steel cylinder of the same dimensions.

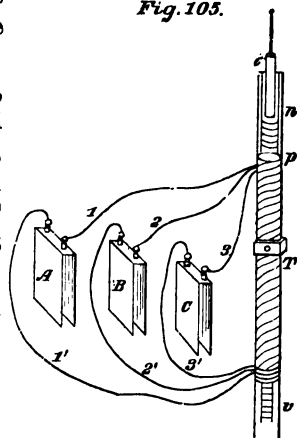
195. Magnetism, then, being a development confined to the surface of magnetic bodies, we require to determine its intensity in respect to the quantity developed and the extent of surface over which it is disposed. In reviewing the deductions bearing on the law of magnetic at-

traction, it may be observed that the reciprocal force is always as the square of the induced magnetism; that is to say, as the square of the quantity of magnetism brought into operation. Thus, where the force is in the inverse duplicate ratio of the distance, when induction $= n$ we have force represented by $a b$; when n becomes $2 n$, force $= 2^2 a b$; when n becomes $3 n$, force $= 3^2 a b$, and so on; that is to say, whilst the inductions or quantity of magnetism developed are 1, 2, 3, &c., the reciprocal forces of attraction or intensities are 1, 4, 9, &c. The same is observable in any of the other laws of force. Take, for example, the case in which the force is as the cubes of the distances inversely (184); when induction $= n$, force is $= a b$; when n becomes $2.83 n$, we have force $= 2^3 a b = 8 a b = 2.83^2 a b$; when n becomes $5.2 n$, force is $3^3 a b = 27 a b = 5.2^2 a b$; that is to say, whilst the quantities of magnetism induced are as the numbers 1, 2.83, 5.2, &c., the forces are as the squares of those numbers. We may from this infer that, to arrive at the quantity of magnetism in operation, all other things being the same, we must refer it to the square root of the attraction or intensity.

196. This deduction being a new and important feature of magnetic action, it may be as well to further verify it by something like a direct and quantitative process.

EXPERIMENT 56.—In this experiment let A, B, C (Fig. 105), be three precisely equal and similar voltaic batteries on Smee's principle, each battery consisting of two elements, and charged with dilute sulphuric acid. Let T represent a cylinder of soft iron about 8 inches long and one-half an inch in diameter, attached to a divided scale $t v$, and surrounded by three distinct coils of copper wire covered with silk thread, not superposed, but coiled successively round the iron. Let the extremities of these coils 1 1', 2 2', 3 3', extend to each of the batteries A, B, C, so as to appropriate each coil to a corresponding battery; for example, coil 1 1' to battery A, coil 2 2' to battery B, and so on; the whole being so circumstanced as to admit of an easy connection, and so bring one or more batteries into action at pleasure. Let the iron cylinder T, thus circumstanced, be placed at a given distance $p n$, immediately under the trial cylinder t , suspended from the wheel of the magnetometer, as in the preceding cases; then, as is evident, when either one or more of the batteries A, B, C are brought into operation through their respective coils, the iron T becomes magnetic, and hence arises a reciprocal attractive force between its extremity p and the trial cylinder $t n$, which force is represented in degrees of the graduated arc attached to the instrument. Supposing the batteries to be precisely equal and similar, and each to develop the same magnetic force

Fig. 105.



when taken singly, we may infer that if one battery A, and one coil 1 1', call up one quantity of magnetism considered as a unity of quantity, then two batteries A + B, and two coils 1 1' + 2 2', taken conjointly, will develop two quantities; three batteries and three coils will produce three quantities. To determine the law, therefore, as regards quantity, it only remains to observe the forces of attraction corresponding to these several developments.

The experiment thus carried out gave the following series of results, the distance $p n$ being regulated at six-tenths of an inch:

Batteries or quantity of magnetism	1	2	3
Force in degrees.....	4	17	37

We may here perceive that the intensity (force) is as the square of the quantity of magnetism, or very nearly; being precisely the same law as that deduced for electrical charge. To obtain, therefore, the relative quantity of magnetism in operation, we must take the square roots of the respective intensities, the magnetic surface and all other things being the same.

197. Although this law appears pretty evident as respects the amount of magnetism in the same or equal magnets, we still require much further investigation of the law of intensity as regards dissimilar magnetic bodies of variable size and surface. The conformity of the previous law of magnetic charge with that of electricity would lead to the conclusion that the law of surface was also the same, and that the intensity would be as the square of the surface inversely; that is to say, the same quantity of magnetism developed upon a double surface would have only one-fourth the intensity. In the present state of magnetic research we can only look to this as being a highly probable result; since we have not any direct methods of experiment, as in electricity, by which such a law can be fairly verified, we require, in fact, to change the surface without interfering with the magnetism. Now this is not easily accomplished; if, as in Experiment 58, we entered the surface, we are likely at the same time to change the amount of induced magnetism, and we get a mixed result; or if, in the last Experiment 59, we increase the dimensions of the iron cylinder T, we are not sure that the quantity of magnetism will remain the same. Until, therefore, some further means of investigating this question by experiment are at our command, we must be content with considering the law of charge as regards surface in the light of a high degree of probability.

Supposing these laws of magnetic charge so far established, we may conclude that if the respective intensities of two similar magnets, the surfaces of which are to each other in a given ratio, say as 1:2 be the same, then the quantities of magnetism in each will be in the same ratio, that is, also as 1:2; for whilst the intensity increases with the magnetism, it decreases with the surface; and hence with twice the quantity of magnetism upon twice the surface, it remains unchanged; being precisely the same law as that of the accumulation of electricity on

coated glass, in which the intensity of a whole battery is no greater than that of one of the elementary jars taken singly.

198. We must not, however, confound this result with a collection of charged jars, or a combination of magnetic bars, each jar or magnet operating independently of the others. What is termed a magnetic battery differs essentially from the electrical battery. It is, in fact, a mere assemblage of magnets, the resulting intensity approaching in a greater or less degree the sum of the intensities of the whole series; no one magnet forms, as it were, any part of any other magnet; whereas, in the electrical battery, all the jars are united, as it were, into one great whole through the charging rods; and the intensity is no greater in the whole combination than in any one jar taken singly. To assimilate the action of a number of charged jars with that of a combination of magnets, the jars must be separate, and each brought to operate independently of the others. Imagine, for example, a light-conducting disk, of 6 inches in diameter, poised and suspended from a common balance, then, if we place a small charged jar immediately under it at a given distance, the balance will indicate a given force. Let a second similar jar be now placed by the side of the former; then the attractive force will be twice as great, and so on, until we have filled an area exactly equal to that of the suspended disk. We may further conclude that the relative magnetism, in two precisely similar and equal magnets, will be as the square roots of their respective intensities, as determined by either of the magnetic instruments employed in these researches.

199. *The magnetic curve.*—The two forces developed in a magnetic bar, and resident in its surface, give origin, in operating on each other through particles of ferruginous matter, to certain curved lines of force, as indicated (28), Fig. 15. These lines were originally considered as the “curvature of the magnetic current,” under an impression that they originated in the circulation of a subtle fluid about the poles of the magnet. Although this hypothesis is now but little valued, yet, as observed by Lambert, we must admit the existence of the curves, and may, without any very great violation of language, call them curves of the magnetic current; it is not the name which constitutes the difficulty; whatever name we give them, we have still to determine the nature and properties of the curves.

This very beautiful physical question constitutes, as before observed, the principal feature of Lambert’s fine mathematical paper in the Berlin Memoirs, and has further engaged the attention of several eminent philosophers. Dr. Roget, the talented author of the treatise on “Magnetism,” published by the Society for the Diffusion of Useful Knowledge, has also treated this question with considerable ability. Not only has he given many interesting demonstrations of the fundamental properties of the magnetic curve, but has also described a mechanical instrument for generating them. In referring to Figs. 15, 16, 17, we may perceive that the magnetic curve is either convergent, as in Figs. 15 and 16, or

divergent, as in Fig. 17, according as we employ one or more magnets, and according as we refer the forces to similar or dissimilar poles. If we conceive (Fig. 15) each small particle of iron to be an indefinitely small needle free to move in any direction, it would necessarily arrange itself in a given determinate position in respect of the forces in action.

In fact, it may be demonstrated that, supposing the magnetic force to vary in the inverse duplicate ratio of the distance, the direction of the axis of a magnetic needle, placed at a given distance from the center of the magnet, will be always a tangent to the point of curvature of one of those peculiar oval curves indicated in the figure. Taking, therefore, the ferruginous particles as indefinitely small magnetic needles, we may conceive the line of curvature at any given distance from the center as made up of a series of such small needles. With respect to the curve itself, it may be considered, geometrically, as generated by the movement of two lines $A C$, $B C$, Figs. 106 and 107, termed *radiants*, and

Fig. 106.

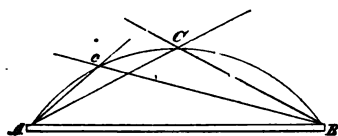
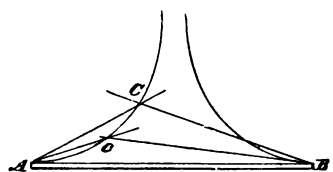


Fig. 107.



which revolve about the poles $A B$, with angular velocities proportional to the varying distances $A C$, $B C$, from the point of intersection C . Let, for example, the two *radiants* $A C$, $B C$, be supposed to turn about the poles A and B , and let them have moved together into the positions $A c$, $B c$; then, if angle $C A c$ be to angle $C B c$ as $A C$ to $B C$, the points $C c$ will be points in the magnetic curve.

The direction of the motion of these *radiants* $A C$, $B C$, may be, as is evident, either in the same or in opposite directions.

When in opposite directions, as in Fig. 106, both the polar angles $C A B$ and $C B A$, increase together, and the curve is convergent; in this case we have a single continuous branch $A C B$. When, however, the *radiants* revolve in the same directions, as in Fig. 107, then, whilst one of the polar angles $C B A$ increases, the opposite angle $C A B$ decreases; in this case the curve is divergent, and finally resolves itself into two divergent branches, as shown in the figure.

The magnetic curve possesses several very interesting geometrical properties, as may be seen in Leslie's elegant work on "Geometrical Analysis; we have not, however, sufficient space to admit of a more general exposition of this subject. According to one of the principal properties of this curve, the sines of the angles made by a tangent and the *radiants*, drawn to the point of contact, are proportional to the square of the *radiants*. Thus, supposing a tangent drawn to the point C (Fig. 106), we should have the sines of the angles formed with $C A$ and $C B :: A C^2 : B C^2$. In the construction of this curve we require to find points in which a small needle being placed, its direction will be a tangent to the curve.

200. We must not conclude our account of these several inquiries into the nature and laws of magnetic force without an especial notice of Professor Barlow's very important investigations of the action of spherical and other masses of iron on the compass-needle, remarkable not only for the precision and elegance of the experiments which they contain, and the mathematical learning and address which they display, but also as furnishing one of those rare examples of physico-mathematical research alike important to the student and to the progress of science.

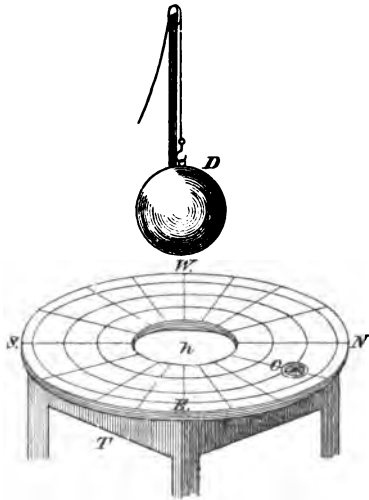
These researches were commenced soon after the appearance of Hanstein's work in 1817, and were undertaken with a view of correcting the errors arising out of the attractive influence of the iron of a ship on the compass.

As a preliminary experiment, an iron shell, such as used in the common howitzer mortar, was placed in different positions about a compass, considered as a center of position, and the deviation of the needle noted both as regarded quantity and direction. *Now it was soon discovered that the deviation depended on the position of the center of the shell in respect of the center of the needle, the shell being elevated or depressed in a given vertical, so as to place its center alternately above and below the needle; the deviations of the needle were observed to be in opposite directions; that is, they were first easterly and then westerly, or reciprocally. Now this happened in every azimuth plane except the plane of the magnetic meridian. IN THIS PLANE THE COMPASS MAINTAINED ITS TRUE DIRECTION.* From these changes in the deviation it followed that, in carrying the shell about the compass, and elevating or depressing it, in different vertical planes a point would exist in each plane, in which the deviation would vanish, since the deviation could not possibly change from an easterly to a westerly deviation without passing through a point of neutrality. In the azimuth east and west, at right angles to the magnetic azimuth or meridian, the deviation was nothing at the line of intersection of the magnetic with the horizontal plane, that is, in the east and west line. In this line the needle also took its natural direction. Now, it occurred to Professor Barlow that if a great number of points of no deviation were thus determined, they might all be in the same plane, which plane would probably in these latitudes be inclined to the horizon; for, since only two opposite points of no deviation were observed in the horizontal plane, it could not evidently be parallel to the horizon.

201. With a view to a more perfect experimental investigation of this interesting question, Professor Barlow contrived a new form of experiment. His apparatus is represented in the annexed Fig. 108. A plane table T, about 4 feet 8 inches in diameter, fixed on massive pillars, being covered with fine paper, has several concentric circles drawn on it. The circular plane is divided into 144 equal parts by radii drawn to every $2\frac{1}{2}^\circ$ of the circumference, and all parting from one principal diameter N.S, taken in the line of the magnetic meridian. The center of

this table is a distinct circular piece of 18 inches diameter, which may be removed so as to leave an opening for an iron ball or shell, D, weighing about 288 pounds, and hung on a set of Smeaton's pulleys. Things

Fig. 108.



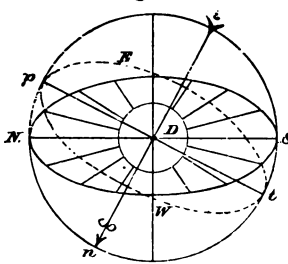
being thus disposed, a compass, C, is placed on one of the concentric circles of about 20 inches radius or distance from the center, and the deviations under the influence of the iron ball D observed at each 5° in different azimuths, that is, in carrying the compass quite round the circle. By elevating or lowering the ball, the height or depth of its center, above or below the center of the compass needle, in the various points of no deviation, could be easily determined. The result of this experiment clearly proved that the points of no deviation are all in the same plane, which plane is inclined to the horizon at an angle of about 20° , being the com-

plement of the angle of the dipping-needle, that is, the quantity required to complete 90° , the dip being about 70° .

It is quite clear that this method of observation is virtually the same as the former (200), the difference being that we circulate the compass about the ball instead of carrying the ball about the compass, and instead of elevating or depressing the center of the needle we raise or lower the center of the ball.

202. It may perhaps facilitate the conception of this extremely beautiful experiment, and the results arrived at, if we suppose the ball D (Fig. 108) to be fixed in the center of the table T, one-half being above, the other half below, the plane of the table, as shown in the next, Fig.

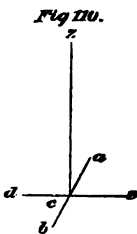
Fig. 109.



109, and then imagine the compass to be circulated about the ball. The experiment would then stand as in Fig. 109. In this figure let NESW be the horizontal plane of the table, D the iron ball. Let sn be the direction of the dipping-needle, Nsn the magnetic meridian, and NS the direction of the horizontal needle. Now we are to suppose the compass to be circulated about the ball D in a circle of a given radius, say 20 inches, and its center

elevated or depressed above or below the horizontal plane at each azimuth of 5° , as the case may be, until the deviation vanishes. In this case the center of the compass would be found to have moved in the plane $\frac{1}{2} E p W$, inclined to the horizon NESW about 20° , and perpendicular to the direction ns of the dipping-needle.

Our conceptions of this experiment may be still further enlarged if, instead of the horizontal needle, we suppose a small dipping-needle to be circulated about the ball, prepared as in the annexed Fig. 110, in which, let $a b$ be a very small magnetic needle, centrally suspended by a delicate thread $z c$, and crossed at the center c by a horizontal index $d e$, consisting of an extremely light reed or a bristle. If this needle be circulated about the ball D (Fig. 109), as before, the index $d e$ will exhibit the same deviations as the horizontal needle, whilst the relative position of the inclined needle in respect of the polar axis $s n$ of the ball D will materially assist our comprehension of the results.



Let us then imagine this needle $a b$ (Fig. 110) to be in the point W (Fig. 109); it will in this point have no deviation; here the line of direction or axis of the needle being parallel to the polar axis $s n$ of the ball, and the line D W joining their centers, being their perpendicular distance, all the attractions upon the needle will balance. Directly, however, we move the needle out of this position, the same conditions do not arise, except the center of the needle move in the plane W p E t. It is only in this plane that the direction $a b$ (Fig. 110) of the needle and the polar axis $s n$ (Fig. 109) of the ball D remain parallel, and their centers always at the same perpendicular distance. We see, therefore, why it is that the points $p t$ in the magnetic, and points E W in the horizontal plane, are points of no deviation. They are, in fact, all points in the plane of equal attraction, or neutrality, as we may also term it.

The east and west points in the horizontal plane are the points of intersection of the two planes. There is, however, this difference between the inclined and horizontal needles when placed in the magnetic plane N s S n; except in the points $p s t n$, the inclined needle varies, in the course of circulation about the ball D in that plane, much in the same way that the horizontal needle deviates in being carried round the ball D in the horizontal plane. Now every point in the magnetic plane is a point of no deviation for the horizontal needle, but not for the dipping-needle; hence, for the horizontal needle we have two planes of no deviation, the inclined plane p E t W and the magnetic plane N s S n. It is, however, the inclined plane which we are to consider as the plane of no deviation *par excellence*, because in this plane neither the dipping-needle nor the horizontal needle deviates, whereas in the magnetic plane there are only four points of no deviation for the dipping-needle, viz, the points p E t W, and these are, after all, points in the plane of neutrality; besides this, the cause of no deviation of the horizontal needle in the magnetic plane is of a very different kind from that of the cause of no deviation in the inclined plane, which has a peculiar and distinctive character.

203. Since the neutral plane evidently cuts the surface of the ball in a great circle $p u t v$ (Fig. 111), the plane of which passes through

the center C , this great circle has been called by Professor Barlow the magnetic equator, the axis and poles of which are coincident with the line sn of the dipping-needle. The hemisphere pnt , below the equator pt , he calls the north magnetic hemisphere, and the opposite hemisphere pst the south magnetic hemisphere. Any point on the sphere is distinguished by its magnetic latitude and longitude, to which end parallels of magnetic latitude and meridians of longitude are drawn, as on the common globes. Extending the plane of these circles, they may be conceived to cut an ideal sphere $pson$, concentric with and surrounding the ball c , and may be hence employed to define the magnetic position of any point in space with reference to the center c of the sphere.

In circulating a compass about the ball in any of these lines or circles, Professor Barlow found, as he had anticipated, that the greatest amount of deviation was in the meridian circle passing through the east and west points; on this account he takes this meridian at his first meridian, and calls its longitude zero. Instead of imagining an ideal astronomical sphere $pson$ to surround the ball c , and in given points of which the compass may be supposed placed, it will be in some cases more convenient to imagine such a sphere to surround the center of the compass placed at c , and suppose the ball moved into certain points of longitude and latitude; the practical result will be evidently the same, and reference may be made to either at pleasure.

204. Very numerous experiments and comparisons between the trigonometrical lines of the angles of deviation and those of the latitude and longitude of the point in which the compass or ball is placed give the following results, and which apply to regular as well as irregular masses of iron:

(1). The longitude being zero, that is, the compass or ball being anywhere in the great circle passing by the east and west points, "the tangent of the angle of deviation is proportional to the sine of the latitude multiplied by the cosine, or to the sine of the double latitude."*

(2). The latitude being constant "the tangent of the deviation is proportional to the cosine of the longitude."

(3). The latitude and longitude being both varied, "the tangent of the deviation is proportional to the cosine of the longitude multiplied into the sine of the double latitude."

If we denote the deviation by Δ , the latitude by λ , and the longitude by l , we have these laws thus algebraically expressed:

$$\begin{aligned}\text{Tan } \Delta &= \sin 2\lambda. & \text{Tan } \Delta &= \cos l. \\ \text{Tan } \Delta &= \sin 2\lambda \times \cos l.\end{aligned}$$

* The product of the sine and cosine of an angle is = to the sine of twice that angle.

The laws of attraction, with respect to distance and force, were found to be as follows:

$$\tan \Delta = \frac{1}{d^3} \quad (\tan \Delta)^2 = F^3 \quad \tan \Delta = F^{\frac{2}{3}}$$

In which the distance is denoted by d and the force by F .

It is to be understood that these laws are only calculated approximately; they are positively correct only for a needle indefinitely small and placed at a limit of distance from the iron ball, such that the magnetism of the needle, and that of the ball, as depending on the induction of its position, may operate on each other in the way of two magnets. *If we bring the needle very near the ball, then the induction of the magnetism of the needle upon the iron is such as to supersede this action; and instead of attracting one pole of the magnetic needle and repulsing the other it will attract either pole of the needle indifferently, or nearly so.*

205. This action of an iron ball on the compass needle, contrary to Professor Barlow's expectations, was found independent of the mass, and to relate only to a small thickness of surface. The following are the results as regarded balls or shells of different magnitudes:

(1). The tangents of the deviations are proportional to the cubes of the diameters of the shells or balls; so that we have, in denoting the diameter by D , $\tan \Delta \propto D^3$.

(2). The tangent of the deviation is as the $\frac{3}{2}$ power of the surface.

Hence, if we denote the surface by S , we have $\tan \Delta \propto S^{\frac{3}{2}}$.

These laws are apparent whatever be the weight or thickness of the shell, provided its thickness be not less than the one-thirtieth of an inch.

Although the conclusion that magnetism resides wholly on the surface of iron bodies appeared satisfactorily established in this kind of action, yet Professor Barlow considers "further experiments necessary to establish the fact." Such experiments we have already adduced (194), and they confirm in a very striking way the truth of this deduction.

CHAPTER VII.

TERRESTRIAL MAGNETISM.

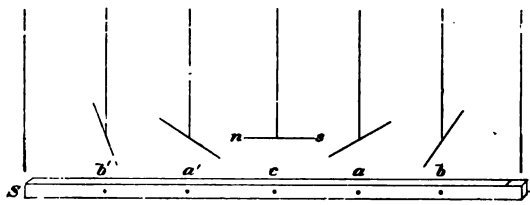
The earth a magnetic body—Variation, dip, and intensity, the three forms of its magnetism—Phenomena of the horizontal, inclined, and oscillating needles—Variation of the compass—Magnetic charts—The three kinds of magnetic lines—Course of the terrestrial magnetic equator—Points of greatest Polar dip—Points of greatest Polar intensity—Position of the magnetic poles—Magnetic disturbances.

206. Comparing the phenomena of the horizontal and inclined needles with those of ordinary magnetic action, we can scarcely avoid the conclusion that the globe of our earth is, upon the whole, a magnetic mass, and that it operates on those needles much in the same way as one magnet operates on another. We have seen that in these latitudes the

position of an evenly poised and freely suspended magnetic bar is not a horizontal position, but an oblique position, the north pole being inclined downward at an angle of about 69° with the horizontal line. Now, if we transport this bar to various parts of the earth, then this angle or dip varies, being nothing about the equatorial regions, where it is horizontal, and 90° in the regions of the poles, where it is vertical, that pole of the bar which turns towards the north being depressed in the northern hemisphere, and the opposite pole in the southern hemisphere. The following experiment is highly illustrative of the magnetic conditions of the phenomenon:

EXPERIMENT 57.—Let N S (Fig. 112) be a magnetic bar 30 inches

Fig. 112.



in length, about one-half an inch thick, and 1 inch wide; we are to suppose this bar regularly magnetic and laid edgewise. Let $n s$ be a short balanced needle of light iron

wire or magnetic steel wire, about 2 inches in length, suspended by a filament of silk immediately over the magnetic center C, so as to be a full length distant from it. At this point the needle will retain its horizontal position, its axis being parallel to the axis of the magnet beneath, and its poles $n s$ in a reverse position to the poles N S of the bar. Under these circumstances, let this small needle be gradually moved along and over the magnetic surface N S; we shall then find it take different degrees of inclination, the inclination being greater as we approach either pole N, S, at which points it will be 90° . We shall further observe, in the course of this experiment, that the south pole s dips on the north polar side of the center C, and the north pole n on the south side. We have here only to conceive the longitudinal magnet N S to represent a portion of the earth's surface extending between the polar regions, and we have a series of phenomena very analogous to those of the direction and dip of the magnetic needle.

The magnetism acquired by a bar of soft iron when placed in a given position is further indicative of the magnetic state of our planet. We have already seen that in placing a bar of soft iron in the position of the dipping-needle, it is immediately rendered sensibly magnetic; the lower extremity in these latitudes being a north pole, and the upper extremity a south pole. If the experiment be tried in the southern hemisphere, then the lower extremity becomes a south pole, and the upper extremity a north pole. Now, this is as near an approach to magnetic induction as can be well imagined.

207. This magnetic condition of our planet, from whatever source derived, becomes more fully revealed to us through the medium of three classes of phenomena, viz, variation, dip, and intensity; these are the three great forms of the earth's magnetism. The absolute values of

these elements, the changes to which they are subject, together with their mutual relations and dependencies, have now become the great objects of investigation; we may add to these certain irregular disturbances by which these elements are occasionally influenced, and which are more especially traced by means of the magnetic instruments and observatories already adverted to. In order, therefore, to investigate the magnetic condition of the earth, we require to know:

(1.) The declination or variation of the horizontal needle, by which we determine its correct position or direction at any given place.

(2.) The inclination or dip, by which we determine the true line of direction of the magnetic force.

(3.) The number which represents the ratio of the intensity of the force at any given place to some comparative unit by which we trace the general magnetic condition of the terrestrial surface.

208. The changes to which the earth's magnetic force is subject may be distinguished by the terms secular, periodical, and irregular. Secular changes are such as are slowly progressive, and which run through a certain course in very long periods of time, returning finally to their original value. Periodical changes are certain regular changes or variations, happening in short periods of time, such as a day, a month, or even a year. Irregular changes are such as cannot be traced through any uniform course, and which are not apparently subject to any given law.

209. In pursuing this most important physical subject, we cannot do better than commence with the phenomena of the horizontal needle. Did the magnetic compass everywhere coincide in direction with the geographical meridian, and were its direction invariable, it would be one of the most simple and valuable instruments ever constructed; such, however, is not the case; its direction is not everywhere the same; it seldom coincides with the true meridian, and is besides subject to a variety of periodical and other variations.

The angular deviation of the compass from the true meridian, termed the declination or variation of the magnetic needle, was certainly known to the Chinese so long since as the commencement of the twelfth century. Keoutsung-chy, a Chinese philosopher, who wrote on subjects of natural history about the year 1111, states that "the magnetic needle declines towards the east, and hence does not point straight to the south, but is only five-sixths to the south." Père Amiot, who resided at Pekin about the year 1780, remarks, in confirmation of this, and in reference to the north pole of the magnet, "The magnetic needle still persists in this capital in pointing 2° and $2^{\circ} 30'$ towards the west, which is still a peculiarity of this country." The Chinese say, in reference to the south pole, that "the needle declines eastward 2° and $2^{\circ} 30'$; that it is never more than $4^{\circ} 30'$, and never less than 2° ." An old manuscript in the University of Leyden, written in 1269 by Peter Adsiger, also notices the phenomenon of an east declination in the north pole of the needle. The great Venetian pilot, Sebastian Cabot, in the service of

Henry VII of England, also Gonzales Oviedo, and the celebrated Columbus, and other early enterprising navigators, all observed the variation of the compass from the true meridian; indeed, it could scarcely have escaped their attention, since they pursued tracts in the course of which the needle must have changed more than two points. The fact appears to have caused no small confusion and anxiety amongst the sailors who accompanied Columbus in his first voyage to America, the needle having hitherto been always supposed to point true north. It appears by Irving's most interesting work, that, on the 13th of September, 1492, Columbus at nightfall found his needle pointing 6° to the west of the polar star. He again examined this deviation the next night, and found it to increase as he advanced—a circumstance which caused the greatest consternation and alarm: "it seemed as if the laws of nature were changing, and that the compass was about to lose its mysterious power." Columbus, however, quieted the fears of the pilots by telling them that the needle had its daily changes round the pole, like the heavenly bodies. It is not a little remarkable that, notwithstanding the frequency of these observations, mathematicians and others of that time who adhered to the system of the Aristotelian philosophy, gave little or no credence to these accounts, considering the thing impossible. At length, however, repeated observation no longer allowed the mere abstract philosopher to maintain the discussion, and in 1556 the declination of the compass was fully received by Spanish writers on navigation as an established fact.

210. The first well-authenticated observations on the variation of the compass in England are to be found in a work by Borough, Comptroller of the Navy, in 1581; as also in a work by Norman, of the same date. They state, from observations at Limehouse in 1580, that the declination was at that time $11^{\circ} 15'$ east. In the early part of the following century, Professor Gellibrand found the declination to be only $4^{\circ} 5'$ east; and in 1657 it appears to have vanished altogether. From that time to the year 1660 the magnetic needle did not sensibly deviate from the true meridian. About five years subsequently to this (viz, in 1665) the direction of the needle appears to have become about a degree and a half west of the meridian; and this westerly declination went on increasing up to the year 1818, since which time the needle has been again approaching the true meridian. The following table contains the declination, with the mean rate of motion as referred to certain periods of observation in London between 1580 and 1850, comprising about 270 years:*

	East declin.		Zero.		West declination.			
Years	1580.	1622.	1660.	1692.	1730.	1765.	1818.	1850.
Declination ..	$11^{\circ} 15'$	6°	0°	6°	13°	20°	$24^{\circ} 41'$	$22^{\circ} 30'$
Rate per year.	$7'$	$8'$	$10'$	$11'$	$11.5'$	$9'$	$0'$	$5'$

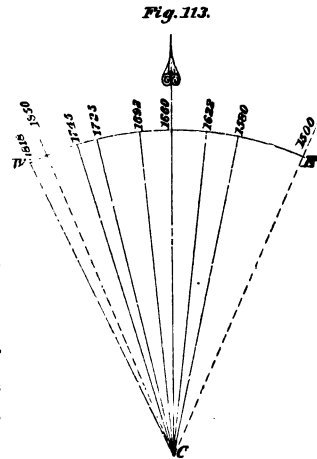
* The rate of movement has been deduced from the average rates of the intermediate periods.

It may be perceived by this table that for a period of eighty years from the first discovery the needle gradually approached the true meridian, and then for a following period of one hundred and fifty-eight years it traveled westward, having at the end of this period attained, in 1818, its maximum of westerly declination, viz, nearly two points and a half of the compass. It has ever since been retrograding, and is now moving again eastward. The mean rates of the movement at the different periods, although deduced from a long interval of years, may not, upon the whole, be far wrong; they serve at least to prove that the motion is not uniform. *In approaching the meridian it has evidently become accelerated, and in approaching the maximum has become retarded;* the present rate of decrease, as deduced by Dr. Lloyd at Dublin, is about 5' annually. Thus it appears that the horizontal needle is subject to a variable oscillation across the line of the true meridian, the period of its westerly movement being about one hundred and sixty years, and the limit of its angular variation $24^{\circ} 41'$. The annexed Fig. 113 represents this angular movement as hitherto observed, the extent of the whole movement being represented by the angle W C E, about 50° , that is, supposing the easterly semi-oscillation to have been equal to the westerly, and the first observations to have been made during the progress of the approach of the needle to the meridian C N, in the year 1580; this would make the total period of one oscillation about three hundred and twenty years.

Observations made at Paris and other parts of the world give similar results; the direction and extent of the deviation, however, are not the same for all places, whilst in particular regions of the globe the needle is found to coincide always with the line of the true meridian. At this present time the declination is west throughout Europe. As we approach very high latitudes, the disturbance in the direction of the magnetic needle is very considerable. Parry, in his first voyage, observed a westerly declination of more than nine points of the compass.

211. A large number of observations on various parts of the earth, from the poles to the equator, on the sea and on land, prove that the lines of direction of the horizontal needle over the earth's surface are not alike, and that these lines are in a constant state of variation, some toward the east, others toward the west.

We are indebted to Halley, who was sent out by the Government of William and Mary to make observations on magnetic declination, for the first attempt to systematize the different variable directions of the magnetic needle. His method consisted in first marking on a general



map of the world all those places in which the declination was nothing, and uniting the whole by a line which he termed the line of no declination. He then traced in a similar way all the points in which the declination was 10° , 15° , 20° , and so on, east or west, thus representing by a magnetic chart the variation of the needle upon the surface of the earth so far as then ascertained, viz, in the year 1700. Many interesting and important results were derived from this system. It was observable, for example, that a line of no variation ran obliquely over North America across the Atlantic Ocean. Another line of no variation descended through the center of China, and passed across New Holland. From which he inferred that these lines had a communication near both poles of the world. Between these lines of no variation—that is, throughout all Europe, Africa, and the greater part of Asia—the declination was observed to be westerly; and on the opposite side—that is, over all the Pacific—it appears to have been at that time easterly. It was further observable that the lines of greatest variation were confined to the polar regions, whilst the least encompassed the globe about the equator.

212. Lines of equal or of no declination, as thus traced on the earth's surface, have been called "Halleyan lines," in honor of their inventor; and more recently "Isogonal lines," or lines of equal angles. The map or chart on which these lines are traced has been termed a "variation chart," and is evidently an invention of no mean importance to the purpose of navigation. The first chart of this kind, constructed by Halley, has necessarily become obsolete, not only from errors arising from the imperfect state of magnetic instruments at the time of the observations, but also from the now known variable state of the earth's magnetism. Halley's chart was first revised by Messrs. Mountain and Dodson, about 1756. Since this period we have had the magnetic atlas of Churchman, up to the year 1800; Hanstein's celebrated chart, published in 1820; and the variation chart and globe of Professor Barlow, which includes the observations of Captain Sir James Clark Ross in the Arctic Seas. The latest chart of this kind is a chart by Erman, who has determined, from his own observations principally, the isogonal lines up to the years 1827 to 1830, throughout the whole length of the Russian Empire. These later productions comprehend, not only the variation, but also the phenomena of the inclination and intensity of the force, and may be hence more properly denominated general magnetic charts than charts of mere variation.

The isogonal lines, as thus laid down on a chart, present to the eye a great variety of complicated flexures; they are seldom parallel to each other; a great portion of them appear to converge towards two points on the earth's surface, one near Baffin's Bay, the other to the southward of New Holland. In Hanstein's chart the isogonal lines exhibit a double convergence in the northern hemisphere toward two points in the vicinity of the pole indicated by the dipping-needle.

213. Beside the great secular or progressive movement (210), the

magnetic needle is found to exhibit a sensible change from month to month, from day to day, and even from hour to hour. This important fact of the daily variation of the needle was first announced in 1722 by Graham, a celebrated optician of London, who observed that whilst the needle was annually changing its direction, its north extremity advanced westward in the early part of the day, and returned again in the evening eastward to the same position. The amount of this daily variation amounted, then, to about half a degree. Since this time the fact has been completely investigated by very refined means of observation, and the following general results arrived at: The north pole of the needle begins between 7 and 8 a.m. to move westward, and this movement continues until 1 p.m. About this time the needle becomes stationary, and soon begins to retrograde east, but with a slower motion than that of its previous advance. About 10 p.m. the needle is again stationary at the point from whence it started. A smaller second oscillation now ensues during the night: the north pole moves slowly west until 3 a.m. and then returns again as before. The action of the sun is undoubtedly the cause of this daily disturbance of the magnetic needle; we may hence expect it to vary in different latitudes both as to time and extent; we require, however, further observation for determining whether the daily variations have the same direction in points of westerly declination as in points of easterly. In the southern hemisphere the direction of the daily oscillation is reversed: the north end of the needle here advances eastward and returns westward.

The annual periodical variation of the needle was discovered by Cassini in 1786, who found that the north pole, from the vernal equinox to the summer solstice, moved eastward, and again retrograded west during the next nine months. This last motion, however, he found to exceed the previous easterly deviation, and constituted the yearly secular change.

The direction of the horizontal needle is in no degree affected by its energy as a magnet, whether possessing a strong or weak magnetic power; still its direction and all the laws of its variation remain the same, at least so far as hitherto observed.

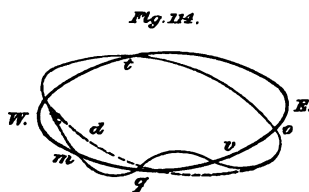
214. *Phenomena of the inclined needle.*—The series of magnetic phenomena of the earth's magnetism which next claim our attention are those of the magnetic dip or the inclination. Mr. Robert Norman, a celebrated optician of London, about the year 1756, having accurately poised some small compass-bars before touching them with the magnet, found subsequently that when rendered magnetic they all lost their balance and assumed a certain angular position in regard to the horizon, so much so that the fly or card attached to them required a counterpoise. This most important discovery naturally excited very intense interest, as materially affecting the mariner's compass, and led the discoverer to construct an instrument by which the full amount of this inclination could be correctly estimated, and which he found at that time in Lon-

don, viz, in 1756, to be nearly 72° . We have already described the nature of this instrument, termed the dipping-needle; we have now to consider its practical application to the purposes of scientific discovery.

The attention of mariners having become directed to the inclination of the needle, and the fly or cards of the compass as adjusted in London being found to lose their horizontality by a change of latitude, it soon became apparent that the inclination was not everywhere the same, until, as already observed, it was finally found to be least in the equatorial and greatest in the polar regions of the earth. Following out Halley's comprehensive views of lines of equal variation, the next great step in the construction of magnetic charts was the addition of lines of equal inclination; these have been termed isoclinal lines, and portray the course of equal dip in all those parts of the world in which observations have been effected.

215. The magnetic equator.—In uniting in this way all the points in which the inclination vanishes—that is, all the points in which the dipping-needle is horizontal—we trace in the equatorial regions of the earth the course of a most interesting and important circular line, which we may consider as the magnetic equator. This line, as hitherto determined, appears embarrassed by disturbances arising not only from almost unavoidable imperfections in magnetical instruments and the means of observation, but likewise from the presence of ferruginous and magnetic masses in certain portions of the earth itself. Sir James Ross observes of the island of Trinidad: “As a magnetic station, our observations were here utterly useless. Three dipping-needles, placed at only just sufficient distance to insure their not influencing each other, indicated as much as 3° difference of dip.” This appears also to have been the case at St. Helena and all volcanic islands.

The magnetic equator, as hitherto traced from a large mass of observations by Cook, Bayly, Dalrymple, and other navigators, discussed by Biot, Morlet, and Hanstein, would seem to be an irregular circular line crossing the terrestrial equator in at least three, if not four, points. Thus, in the annexed Fig. 114, if we suppose the circle $W t E$ to represent the terrestrial equator, then the irregular circular line $m t o$ may be supposed to be the magnetic equator, evidently portraying



between the points w and o either some great irregularity in the earth's magnetic condition, or the presence of some great disturbing force. From the great regularity in all the

other portion of the curve, we can readily conceive its continued progress through the dotted line d , supposing the sources of disturbance we have adverted to not to exist. Duperry, who crossed the magnetic equator in the Coquille no less than six times during the French expedition of 1822 to 1825, and to whose indefatigable zeal and ability we are

indebted for a most careful investigation of this great physical problem, has given, in the "Annales de Chimie" for 1830 a valuable magnetic chart representing, according to his researches, its general course. Duperry traces this great magnetic curve, from his own observations alone, through an extent of 247° of west longitude, comprising the Atlantic Ocean, part of South America, the great Equinoctial Ocean, or Pacific Ocean, as far as the west side of the island of Borneo. After this he relies on the observations of Colonel Sabine at St. Thomas, in 1822, and of Capt. J. de Blosselville, in the Chevrette, made in 1827. Adopting the eastern node, as determined by Sabine, which he places in longitude $3^{\circ} 20'$ east of the meridian of Paris, in the Atlantic Ocean, not far from the west coast of Africa, the points of no inclination pass through Africa and ascend into the northern hemisphere, probably up to the fifteenth degree of north latitude, so far as the Red Sea; then, descending through the Indian Ocean, they cross the southern extremity of Hindostan, the isles of Malacca, and the northern extremity of Borneo; then, traversing the great Pacific, they cross the equator of the globe in a second point, in about longitude 176° east of Paris; so that, according to this course, the magnetic equator is inclined to the equator at an angle of between 14° and 15° , crossing it in two points nearly diametrically opposite. It is not unworthy of remark that four-fifths of this great circle traverses the vast seas of the equatorial regions. Although the curve is certainly tolerably regular throughout at least one-half its course, yet a large amount of observations for all that portion running through the Pacific from 112° to 270° of west longitude tend to involve it in, inexplicable windings, such as shown in Fig. 114. By a careful analysis of the observations, recorded at long intervals of time, the nodes, or points of intersection of the magnetic and terrestrial equators, have a slow westerly movement.

The isoclinical lines, or lines of equal dip, relative to all that portion of the magnetic equator *W to* (Fig. 114), which appears perfectly circular, are upon the equidistant parallels fairly regular, and the dip pretty constant for the same parallel, at least up to 60° of magnetic latitude. These parallels comprise Europe, Africa, the Atlantic, and the eastern shores of America. Biot, by a refined analysis, has given a formula for the inclination, which appears to represent the phenomena of the dip in some parts of the earth with a fair degree of precision. According to this formula, the inclination of the magnetic needle in any place is twice its magnetic latitude, a deduction first arrived at by Kraft, of St. Petersburg. Thus the magnetic latitude of Quito, in Peru, being $6^{\circ} 33' 10''$, the inclination should be $13^{\circ} 6' 20''$; that is, double this angular quantity. Now, Humboldt gives the dip at Quito, from observation, $13^{\circ} 21' 54''$, which is a fair coincidence. Barlow, considering the magnetic condition of the earth as approaching that of a soft iron ball, arrives at a similar deduction; according to his formula, "the tangent of the dip is double the tangent of the magnetic latitude." *It is, however, very*

doubtful whether such formulæ can be satisfactorily applied to the whole terrestrial surface, more especially in the present imperfect state of these inquiries.

The following table exhibits the inclination of the magnetic needle as determined at a few remarkable places of the globe within a comparatively recent date.

SOUTHERN HEMISPHERE.	
	Dip.
Charlotte Sound	54° 50'
Cape of Good Hope.....	34°
Lima.....	10° 30'
Peru.....	1° 00'
Alexandria	31° 12'
NORTHERN HEMISPHERE.	
	Dip.
Rome	60°
Paris	67°
London	69°
Petersburg.....	71°
Hudson's Bay	69° 57'

It is evident from this table that the magnetic inclination increases as we approach the polar regions.

The isoclinal lines appear to form irregular oval curves, diminishing in magnitude in each hemisphere as they recede from the magnetic equator.

216. The magnetic dip, like the direction of the horizontal needle, is subject to continual and progressive changes, both secular and periodical, and is at this present moment rapidly decreasing. According to the records handed down to us by different observers, the inclination at London in 1576 was 71° 50'. In 1676 it had become 73° 30'. In 1723 it was 74° 42', having here reached a maximum. In 1790 it had decreased to 71° 53'; in 1800 to 70° 35'. In 1821 the magnetic dip, as determined by Sabine, was 70° 3'. In 1830 Captain Kater gives it as 69° 38'. According to the observations made at the Royal Observatory-Greenwich, it is now about 68° 30'; having decreased about 6° 12' in one hundred and twenty-eight years, or at the rate of about 3' each year nearly. If the early observations are to be relied on, the magnetic dip, when first observed by Norman, in 1576, was increasing, and had attained a maximum in 1723, having increased about 2½° in one hundred and forty-seven years; being at the rate of about 1½' annually. Since this it has continually decreased and with increasing rapidity; the mean annual movement from 1830 to 1850 being at the rate of more than 4' each year, whilst the first annual decrease between 1723 and 1790 was only at the rate of about 2.5' annually. Admitting some sources of error in the earlier observations, there is still sufficient evidence of an accelerated and retarded movement in the secular changes of the inclined needle.

The inclination, like the declination, appears subject also to a slight hourly variation; it is, however, very small. According to Hanstein, the inclination is about 4' greater in the morning than in the afternoon.

The inclined needle, like the horizontal needle, is not affected by its power as a magnet as to direction; whatever be the magnetic force, the angle of inclination remains the same under the same circumstances.

217. Needle of oscillation, or magnetic pendulum.—Although the phenomena of the variation and inclination of the magnetic needle portray, under two peculiar forms, the general distribution of magnetism throughout the earth considered as a magnetic body, yet these forms are not so well adapted to convey so definite a view of the magnetism of our planet as would be obtained by an adequate examination of the relative magnetic intensity of different points of its surface. A large number of facts have been adduced to show that a freely-suspended needle in a state of oscillation is influenced by the magnetic force of the earth in a way analogous to that of a common pendulum oscillating by the influence of gravity; and that hence, by means of such a needle, we may determine the ratio of the intensity of terrestrial magnetic force throughout the whole extent of the earth's surface. This method of determining the magnetic intensity in the different regions of our globe was first suggested by Graham, so long since as the year 1775, and was afterwards more fully employed and perfected by Coulomb, Humboldt, and Hanstein. The examination of the earth's magnetic intensity had also, at the instigation of the Royal Academy of Sciences, engaged the attention of the unfortunate La Pérouse, in his expedition to the South Sea in 1785. The results, however, if any, perished with the expedition.

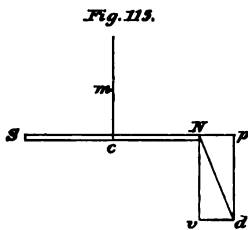
The nature and principle of the instrument more especially adapted as a magnetic pendulum has been already described and explained; and we have seen that the force urging the needle is taken as proportional to the square of the number of vibrations made in a given time. *It is, however, essential to remember that, unlike the horizontal and inclined needles as to direction, this law applies as much to the magnetic force of the needle itself as to the magnetic intensity of the earth—a condition which at once destroys the perfect analogy between a vibrating magnetic needle and a common pendulum oscillating by the force of gravity. That would be the most perfect form of magnetic pendulum which would only involve in the consideration of the force in operation the magnetic force of the earth itself, much in the same way as in measuring the force of gravity by the common pendulum we neglect the small attractive force of the matter of the pendulum, as being infinitely small in comparison with the gravitating force of the earth. If a small needle of perfectly soft iron, not having any polarity of its own, and delicately suspended, could be caused to vibrate across the magnetic meridian at various parts of the earth, solely by the influence of terrestrial magnetic induction, we should then have a magnetic pendulum approaching the condition of the common pendulum; we cannot, however, produce such a result, and we therefore have recourse to needles of tempered steel*

permanently magnetic; that is to say, we give our pendulum an inherent force, so as to put it in a position to operate upon the magnetism of the earth. It still remains, therefore, to inquire what new corrections it may be requisite to introduce into our calculation of the experimental results obtained under this peculiar condition of the vibrating body, more especially when we observe that the magnetic force exerted between opposite and permanent magnetic polarities may vary in a different way from that between a magnet and soft iron, and hence the same law of force between the center and poles of a magnetic bar is not found to obtain when the force is taken between the different points of the bar and a small suspended magnet. The true measure of the earth's magnetic intensity at any point of its surface would be its inductive force on soft iron. This, according to the laws we have arrived at would be as the quantity of magnetism in operation directly, and as the distance inversely. Supposing we could actually measure the reciprocal force between any point of the earth's surface, considered as a magnet, and a given mass of soft iron, without sensible polarity, then, as we have shown, the relative quantity of magnetism in operation, as referred to the earth, is represented by the square roots of the respective intensities or force of the reciprocal attraction.

The method, however, commonly resorted to, of determining the magnetic intensity of any point of the terrestrial surface, is that of the vibrating magnetic bar, as being upon the whole simple and available. It is nevertheless unquestionably open to objection and the results hitherto arrived at by such means are not to be viewed in any other light than that of rough approximations. When we employ this method we must take especial care to operate with the same needle, and with a needle in which the magnetism may be considered as invariable; to insure this it is even found requisite to apply a small correction for changes of temperature.

218. In determining the terrestrial magnetic intensity with the needle of oscillation we may either employ the inclined needle or the horizontal needle, or otherwise the vertical needle. From the circumstance, however, of the greater impediment to motion in the construction of the dipping-needle, the delicately-suspended horizontal needle is commonly preferred, notwithstanding that it involves some final calculation before the total intensity can be determined.

Let, for example, $S N$ (Fig. 115) be a light magnetic bar horizontally suspended by a fiber of silk, m . Let $N d$ be its natural inclination or dip at a certain point of the earth's surface; then taking this line $N d$ to represent the total magnetic force, we may conceive this force to be the equivalent or resultant of two other forces, one ($N p$) acting in the horizontal direction $S N$ of the needle, and the other ($N v$) acting in the vertical, or direction perpendicular to the line of the needle. These two forces have been termed the hor-



horizontal and vertical components of the terrestrial magnetic force, such as it is, found under any inclined or natural direction, $N \bar{d}$. If, therefore, we take the oscillations of the dipping-needle as a measure of the intensity, we may suppose the oscillations to result from the whole $N \bar{d}$ of the terrestrial magnetic force, since the needle vibrates across the line $N \bar{d}$, or line of its natural direction; but if we take the oscillations of the horizontal needle as a measure of the intensity, then, as is evident, the vibrations do not result from the action of the whole of the terrestrial magnetic force $N \bar{d}$, but only from that part of it ($N p$) acting in the horizontal line of the needle, and which will be greater or less according as the direction is more or less inclined to the horizon. Now, it is easy to see in the above Fig. 115 that, taking $N p$ to represent the horizontal component of the total force $N \bar{d}$, we have $N p = \cos$ of angle $p N \bar{d}$; that is to say, the cosine of the dip. So that calling total force $N \bar{d} = R$, and the horizontal force or component $N p = r$, we have $r = R \times \cos$ of dip, the cosine of the dip being the function of the obliquity which represents that portion of the whole force acting on the horizontal needle. We may arrive in a similar way at the total intensity by means of the vertical component $N v$; that is, by observing the oscillations of a vertical needle. In this case, however, we have to take into account the vertical force $N v = p \bar{d} = \sin$ of the angle or dip $p N \bar{d}$, which, calling the vertical force $= S$, gives $S = R \times \sin$ of the dip. The first of these methods, however, is usually preferred; and from this we obtain

$$R := \frac{r}{\cos \text{ of dip.}}$$

219. We are indebted to the indefatigable Humboldt for the first practical results of the application of the needle of oscillation to the investigation of the variable magnetic intensity of the earth. Having carefully determined the time of a given number of oscillations of a small magnetic needle at Paris, he transported the same needle to Peru, and again examined its rate of vibration; the result was, that whilst this needle performed at Paris 245 oscillations in ten minutes, it only made at Peru 211 oscillations in the same time. The relative intensities, therefore, were as $245^2 : 211^2$, that is, as 1.3482 : 1; or, calling the intensity at Peru, a point of the magnetic equator, unity, then the force at Peru and Paris would be as 1 : 1.3482.† This kind of experiment has since been extended to almost every known part of the globe; the result has been a series of numbers representing the ratio of the terrestrial magnetic intensity to a given unit for every point of the earth's surface.

† At the time when Humboldt made this experiment, an opinion prevailed that the intensity was the least where the dip was zero; it was on this account that Peru was taken as unity. Some doubts, however, have since arisen upon this point; still the scale assumed by Humboldt is usually resorted to; hence, to express intensities less than that of the magnetic equator, we must employ numbers less than unity.

The following table may be taken as an illustration for a few remarkable places:

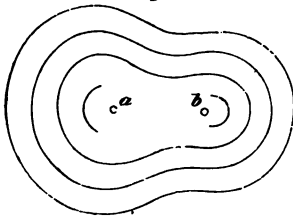
	Intensity.
A little W. of St. Helena	0.743
Rio de Janeiro	0.887
Cape of Good hope	0.945
Peru	1
Isle of France	0.096
Naples	1.274
Paris	1.348
Berlin	1.350
London	1.369
Baffin's Bay	1.707

It appears by this table, as first announced by Humboldt, that the intensity is least about the equatorial regions of the globe, and greatest in the polar regions. By the indefatigable labors of Hanstein, Erman, and a few other observers, we are in possession of a table of intensities for a large portion of the terrestrial surface.

220. If we connect all those points in which the terrestrial magnetic intensity as thus deduced is the same, we arrive at a series of lines termed "isodynamic," or lines of equal power. These lines, according to Sabine and others, are not always parallel to the isoclinal lines; the differences, moreover, are systematic. It has been further inferred, from a chart of these lines, that the points of greatest and least intensity are not indetical with the points of greatest and least inclination; the intensity, therefore, of the magnetic equator may not be everywhere the same.

Although these isodynamic lines are still rough and incomplete, yet we cannot doubt of their being curves of double curvature returning into themselves. In Siberia and the Pacific, toward the polar regions, they are found, according to Hanstein and Erman, to consist of a system

Fig. 116.



of double loops, as it were, inclosing two polar points. The annexed Fig. 116 may be taken in the way of approximation to the form of these loops, in which *a b* are the points or poles of the system. Hanstein places the western of these intensity poles near Hudson's Bay, in latitude 50° north, longitude 90° west; and the other, eastern or Siberian pole, in probably about 70° north latitude and 120° east longitude. In the southern hemisphere the loop form of the intensity lines and the two intensity poles are more fully developed as we recede from the equator. The two southern points have been placed, one to the south of New Holland, in latitude 60° south, longitude 140° east; the other in the South Pacific Sea, also in latitude 60° south, but longitude 120° west. These four poles, therefore, are not diametrically opposite each other. The intensity of the North American pole and that of the southern pole,

near New Holland, are nearly alike, being both about 1.8; as are also those of the Siberian and South Pacific poles, which are about 1.7. The two polar intensities, therefore, in each hemisphere, are of unequal force. Both the isoclinal and isodynamic lines would appear from these investigations to inclose two foci or points of greatest attraction, the bends or flexures of the curves being less marked as we approach the equator.

On comparing the observations of Sir James C. Ross with those of Erman, we find that the terrestrial magnetic force towards the south pole increases nearly in the ratio of 1 : 3. Since, upon a discussion of all the best observations, it appears that the maximum may be taken as 2.052, the minimum as 0.706; both these are found in the southern hemisphere. The ratio of the maximum to the minimum force, then, is as 1 : 2.9 nearly, or nearly as 1 : 3. From the profound inquiries of Gauss, it appears that the total and absolute terrestrial magnetic force, considering the earth as a magnet, is equal to six magnetic steel bars of a pound weight, magnetized to saturation, for every cubic yard of surface. Compared with one such bar, the total magnetism of the earth is as 8,464,000,000,000,000,000 : 1, a most inconceivable proportion.

The terrestrial magnetic force, as thus deduced by the needle of oscillation, like the elements of declination and dip, is subject both to secular and periodical changes. The amount of the secular change is not yet determined, according to Hanstein; however, the intensity is gradually declining throughout Europe. Sir James Clarke Ross, from observations on board the *Erebus* in 1839, concludes that the line of least intensity had advanced considerably northward.

The periodical and diurnal variation, as hitherto observed, gives a maximum of intensity between 9 and 10 p. m., and a minimum between 10 and 11 a. m. The monthly variation evinces a maximum in December and a minimum in June.

The greatest change or difference in the annual intensity of the northern hemisphere is about 0.0359.

221. The needle of oscillation is not the only means employed for determining the magnetic intensity of the earth. Gauss resorts, for example, to a statical experiment, which consists in deflecting a magnet, delicately suspended by a silk filament from its meridian, by means of a second magnet, and from which he conceives the absolute intensity may be derived. Mr. Fox determines the earth's intensity by means of weights applied on his dipping-needle deflector to balance the dip.

Variations in intensity are measured by the bifilar and vertical force magnetometers, as also by a species of steelyard balance contrived by Professor Lloyd.

222. *Position of the terrestrial magnetic poles.*—The first step in the generalization of the phenomena of the declination of the magnetic needle is due to Halley, who conceived the notion of four terrestrial magnetic poles, two in each hemisphere, one fixed, the other in motion. The north pole nearest to England, he places in latitude 83° north, longitude

about 5° west of Greenwich; the other in latitude 75° north, longitude 115° west. The two southern poles he places, one in latitude about 74° south, longitude 95° west; the other is about 70° south latitude, and longitude 120° east. These positions he thinks consistent with the then observed direction of the magnetic needle in various places. Churchman, in his Magnetic Atlas, only traces two poles, one in latitude 58° north, longitude 134° west; the other in latitude 58° south, longitude 165° east. Hanstein, from his magnetic chart of variation, dip, and intensity, is led, with Halley, to infer the existence of two poles of unequal power in each hemisphere, towards which the isogonous lines appear to converge by two separate systems in each hemisphere. The stronger north pole he finds above the American continent, in latitude 70° north, longitude 92° west; the weaker he places in the Arctic Ocean, in latitude 85° north, longitude 140° east. The stronger south pole he places in latitude 69° south, longitude 142° east, not far southwest of Van Diemen's Land; the weaker south pole is in latitude 79° south, longitude 136° west, being southwest of Terra del Fuego. These four poles, therefore, are at present nearly diametrically opposite; their precise position, however, is subject to a great secular change. Did we infer the position of the magnetic poles from the course of the magnetic equator, considering them as the extremities of the axis of this great circle, we should find the north magnetic pole in Greenland, a little beyond Baffin's Bay, latitude 78° , longitude 60° west; and the south magnetic pole in the Antarctic Sea, latitude 76° south, longitude 130° east. The precise position and course of the magnetic equator, however, are still involved in doubt; which, together with the apparently uncertain and irregular distribution of the earth's magnetism, forbids our placing any great confidence in the position of the two magnetic poles, as thus deduced.

By observations with the dipping-needle on board H. M. ship *Brazen*, in May, 1813, a point approaching verticity was found in Hudson's Bay, in latitude 69° , longitude 92° west. Parry in August, 1819, was to the north of this, and found the dip $88^{\circ} 37'$. The position of the pole, from his subsequent observations, would be in about latitude 71° , longitude 93° west. In 1832, the observations of Sir James C. Ross completely confirmed the close approximative position of this point of polarity. This celebrated navigator found the dip near Prince Regent's Inlet, in the great American continent, latitude 70° north, longitude 96° west, to be within one minute of 90° , and which coincides wonderfully with Hanstein's deduction. Barlow also observes: "This is precisely the point in my globe and chart in which, by supposing all the lines to meet, the several curves would best preserve their unity of character as a system." So far, therefore, we have confirmed by observation the position of at least one point of verticity of the dipping-needle in the northern hemisphere. Gauss, whose enlarged, profound, and comprehensive views of terrestrial magnetism have so long commanded the attention of European science, has endeavored, from certain theoretical considerations, to

doubt the existence of more than a single pole in each hemisphere, one of which he places in about latitude $73^{\circ} 35'$ north, longitude 95° west, the other in about latitude $72^{\circ} 30'$ south, longitude 152° east. Both these points are not far from the results of observation.

Professor Barlow, following out his formula for the dip, viz, tangent $\delta = 2$ tangent λ , and, considering the magnetic condition of the earth as being analogous to that of a simple iron ball or shell, is led to conclude that each point of the terrestrial surface has its own particular polarizing axis, the extremities of which fall probably in all cases within the polar circles. These are the least limits we can at present assign them. There is consequently, he says, no particular spot in the polar regions, which may, *par excellence*, be taken as the magnetic pole; if there were, he imagines it might, by the above formula, be easily computed, whereas, on subjecting the observed elements to calculations, he found discrepancies of no less than 10° of latitude and 55° of longitude. Observation, however, still confirms the notion of a point of verticity for the dipping-needle.

223. Magnetic storms.—Besides the secular and periodical variations of the magnetism of the earth, as indicated by the phenomena of the horizontal and inclined needles, we also find these needles subject to certain irregular variations, uncontrolled by any apparent law. It is to the illustrious and indefatigable Humboldt that we owe all our first knowledge of such perturbations. Being engaged at Berlin, in 1806 and 1807, in examining the changes in the declination of the needle for every half hour, his attention was called to certain capricious agitations in its position, not referable to any accidental or mechanical cause, and which occasionally caused so great an oscillation as to lead him to refer them to a sort of magnetic reaction, propagated from the interior of the earth. He accordingly designates these disturbances as “magnetic storms,” as being analogous to the sudden changes of electric tension which ensue in the electric storms of the atmosphere. During these storms the needle is observed to be affected by a sort of shivering motion, and to oscillate several degrees on each side of its mean position. In 1818, further observations were made simultaneously by Arago at Paris, and Kupffer at Kassin, in Russia, which showed, in a satisfactory way that these perturbations, announced by Humboldt, occurred in both places at the same instant of time, notwithstanding that the places of observation were separated by 47° of longitude. Full attention being at length called to this subject, Humboldt, in 1830, succeeded in establishing magnetic observatories in various parts of Russia, which have since been extended to other parts of the world, constituting such a network of inquiry into all the great facts of terrestrial magnetism as would have been but a few years before difficult to imagine. Since the year 1828, from Toronto, in Upper Canada, to the Cape of Good Hope and Van Diemen’s Land, from Paris to Peking, we find magnetic observatories, all established under one uniform system, and carrying on sim-

ilar and simultaneous observations. The principal magnetic instruments employed in these observatories have been already described, and from continuous observations, carefully registered, in almost every country of the globe, we are presented with the startling fact of an unceasing series of what may be termed terrestrial magnetic pulsations, extending simultaneously over an interval equal at least to the whole breadth of Europe, and perhaps over the whole terrestrial surface. "When," says Humboldt, "the tranquil hourly motion of the needle is disturbed by a magnetic storm, the perturbation frequently proclaims itself over hundreds and thousands of miles simultaneously, or is propagated gradually in brief intervals of time in every direction over the surface of the earth."

224. Beside these magnetic disturbances referable to some hidden and sudden change in the condition of the earth's magnetism, we find other singular disturbances in the position of the magnetic needle at the instant of the appearance of the aurora borealis, or northern lights. This fact was especially noticed and studied by Dalton so long since as the year 1793, who observed that the luminous beams were parallel to the dip, and the arches at right angles to the magnetic meridian. This disturbance of the magnetic needle consists in an irregular oscillation sometimes to the eastward, and then to the westward of its mean direction. The greatest amount of disturbance is when the aurora is in the zenith. Hanstein also, who has studied this phenomenon, says that the shivering movements of the needle never perhaps occur except at the time of an aurora, and that the disturbances are felt at the same instant of time in places widely separated; the extent of the movement may, in twenty-four hours, amount to between 5° and 6° . Arago thinks that the aurora disturbs the needle even before the light shows itself in the horizon. The auroras which are only visible in America and Siberia are, he says, found to affect the magnetic needle at Paris. It is not improbable that the presence of an aurora and the disturbance of the magnetic needle are both effects of the same or a similar cause, so that we cannot assume the presence of the aurora as the active force; we should rather regard it as an accompanying phenomenon; more especially as we find, according to Captain Foster's observations at Port Bowen, that during certain auroras the magnetic needle remains undisturbed. It has been further shown experimentally, that the magnetic oscillations are unaffected by the presence of a powerful column of mere electrical light flashing through an exhausted receiver 6 feet high and 4 inches in diameter.

Halley, more than a century since, considered the aurora to be a magnetic phenomenon, a conjecture which bids fair to receive complete confirmation. According to Humboldt, the aurora may be considered as a terrestrial magnetic activity raised to the intensity of a luminous phenomenon, one of the sides of which is the light, the other the disturbance of the needle; so that this magnificent appearance may be considered as the act of discharge at the conclusion of a magnetic storm.

CHAPTER VIII.

TERRESTRIAL MAGNETISM (continued).

Great recent progress of the science—Reports of the Committee of Physics and of the Joint Committee of the Royal Society and British Association—Observations taken at the observatories of Kew and Greenwich—Variations of the magnetic dip in London.

225. The two chief branches into which the science of terrestrial magnetism in its present state may be divided, may be stated to be these: (1.) Observations on the actual distribution of the magnetic influence over the globe at the present epoch in its mean or average state, when the effects of temporary fluctuations are either neglected or eliminated by extending the observations over a sufficient time to neutralize their effects; (2.) The history of all that is not permanent in the phenomena, whether it appear in the form of momentary, daily, monthly, or annual change and restoration; or in progressive changes not compensated by counter changes, but going on continually accumulating in one direction, so as in the course of many years to alter the mean amount of the quantities observed.

With reference to the first of these two branches, the report goes on to state:

The three elements, viz, the horizontal direction, the dip, and the intensity of the magnetic force, require to be precisely ascertained before the magnetic state of any given station on the globe can be said to be fully determined * * * and as all these elements are at each point now ascertained to be in a constant state of fluctuation, and affected by transient and irregular changes, the investigation of the laws, extent, and mutual relations of these changes is now become essential to the successful prosecution of magnetic discovery.

With reference to the second branch, viz, the secular and periodical variations, it is observed that—

The *progressive and periodical* being mixed up with the *transitory* changes, it is impossible to separate them so as to obtain a correct knowledge and analysis of the former without taking express account of, and eliminating the latter.

And with reference to the secular changes in particular, it is remarked:

These cannot be concluded from comparatively short series of observations without giving to those observations extreme nicety, so as to determine with perfect precision the mean state of the elements at the two extremes of the period embraced, which, as already observed, presupposes a knowledge of the *casual* deviations.

With regard to the phenomena designated “casual variations,” all that was known was that there occurred occasionally, and, as it was supposed, irregularly, disturbances in the horizontal direction of the needle, which were known to prevail with an accord which it was impossible to ascribe to accident, *simultaneously* over considerable spaces of the earth’s surface, and were believed to be in some unknown manner connected, either as cause or effect, with the appearances of the

aurora borealis. The chief feature by which the presence of a disturbance of this class could be recognized at any instant of observation—or by which its existence might be subsequently inferred independently of concert or comparison with other observatories—appeared to be the deflection of the needle from its usual or normal position to an amount much exceeding what might reasonably be attributed to irregularities in the ordinary periodical fluctuations. The observations which had been made on the disturbances anterior to the institution of the colonial observatories had been chiefly confined to the declination.

For the discussion of the laws of “irregular” changes, the magnitude of the departure from the usual or normal state at the instant of observation was made available, and the observations taken at Toronto, Hobarton, and St. Helena have furnished data for the investigation at three points of the earth’s surface—one in the temperate zone of the *northern* hemisphere, a second in the temperate zone of the *southern* hemisphere, and a third in the tropics—of the laws, extent, and mutual relation of these transient or irregular changes as affecting the three magnetic elements, viz, the declination, the inclination, and the total force.

One of the results of this investigation is, that the phenomena of this class, which may be termed “occasional,” are in their mean or average effects subject to periodical laws of a very systematic character; placing them, as a first step towards an acquaintance with their physical causes, in immediate connection with the *sun* as their primary cause. They have (1) a *diurnal* variation, which follows the order of the solar hours and manifests therefore its relation to the sun’s position as affected by the earth’s rotation round its axis; (2) an annual variation connecting itself with the sun’s position in regard to the ecliptic; (3) a third variation, which seems to refer still more distinctly to the direct action of the sun, since, both in period and in epochs of maximum and minimum, it coincides with the remarkable period of about ten or perhaps more nearly *eleven* of our years, the existence of which period has been recently made known to us by the phenomena of the solar spots, but which, as far as we yet know, is wholly unconnected with any thermic or physical variation of any description (except magnetic) at the surface of the earth, and equally so with any other cosmical phenomena with which we are acquainted.

Now that it is become known that these “casual perturbations” are governed by periodical laws, and that these laws and those of the regular “periodical variations” are dissimilar in their epochs, it is manifest that, in their joint and undivided effects, we have two variations due to different causes and having distinct laws superimposed upon each other. To know the one correctly, we must necessarily, therefore, eliminate the other.

A careful analysis of the solar-diurnal variation of the declination at the colonial observatories has brought to light the existence at all the stations of an *annual inequality* in the direction of the needle, concurrent

with changes in the sun's declination, having its maxima (in opposite directions) when the sun is in or near the opposite solstices, and disappearing at or near the epochs of the equinoxes. An intercomparison of the results of analysis at these stations has shown that this inequality has the remarkable characteristics of having notably the same direction and amount in the southern as in the northern hemisphere, and in the tropical as in the temperate zones.

226. In August, 1857, a committee, consisting of the president of the British Association, the Rev. Dr. Robinson, and Major-General Sabine, co-operating with the president and counsel of the Royal Society, was appointed to take steps for procuring a continuance of magnetic and meteorological observatories in the British colonies. In their report the committee state, as the most important results of the discussion, as far as it had then gone, of the accumulated observations at the observatories at St. Helena, Toronto, Hobarton, and the Cape of Good Hope as follows:

1. The mean state of the several magnetic elements for each station, viz, dip, declination, and intensity, as reduced to a fixed epoch, has been obtained with precision.

2. The rate of progressive secular change has been determined with precision in all the elements.

3. The laws of diurnal, annual, and other periodic fluctuations in the value, of the elements have been established, with such a precision as to open views of magnetic action of a singular and unexpected character, for it has been demonstrated that the systems of the diurnal and annual magnetic changes may be separated into two perfectly distinct and physically independent systems: (1) the one at any particular station holding its course according to laws depending solely on the sun's hour-angle at the moment of observation, and his meridian altitude at different seasons; (2) the other comprehending all those movements which, under the name of "magnetic storms," or "irregular disturbances," have hitherto presented the perplexing aspect of phenomena purely casual.

The sun's regular action on the magnetism of the globe has been shown to be referable, in the first place (and for one of its arbitrary coefficients), to the geographical situation of the place of observation with respect to a certain line of equator on the earth's surface, and in the next place to the fact of the sun's having a north or south declination; so that the whole diurnal change in any one of the elements, and at any station, is made up of two portions, one of which retains the same sign, and a constant coefficient all the year round; the other changes sign and varies in the value of its coefficient with the annual movement of the sun from one side of the equator to the other; that consequently for a station on the magnetic equator so defined, the mean amount of diurnal change is *nil*, when taken over the whole year, but in any particular day in the year it has a determinate magnitude which passes through an annual periodicity with opposite characters in oppo-

site seasons. And that for a station in middle latitude the mean diurnal fluctuation is not *nil*, but such as during every part of the year to exhibit an *easterly* deviation in the morning hours, and a *westerly* deviation in the evening hours, for stations *north* of the magnetic equator, and *vice versa* for the south of it, but that the amount of this deviation or the amplitude of the diurnal fluctuation varies with the seasons, being exaggerated or partly counteracted by the alternate conspiring and opposing influence of the sun's declination during the summer and winter seasons.

As regards the *irregular* disturbances, they are found to conform in their average effect at each of the twenty-four hours of the day, and on each day of the year to the very same rules as regards the sun's daily and annual movement, with one remarkable point of difference, viz:

That their hours of maxima and minima are not identical with those of the regular class, but that each particular station has in this respect its own peculiar hours analogous to what is called the *establishment of a port* in the theory of tides, and that in consequence, the superposition of these two systems of diurnal fluctuation gives rise to a system of compound variations analogous to the superposition of two undulations having the same period, but different amplitudes and different epochal times, and that by attending to this principle many of the most complex phenomena, such as that of a double maximum and minimum, with the occurrence of a nightly as well as a daily movement, are explained in a satisfactory manner.

The discussion of the observations made in the colonial magnetic observatories up to 1857 has also fully established the existence of a very extraordinary periodicity in the extent of fluctuation of all the magnetic elements, and in the amplitude and frequency of their irregular movements especially, which connect themselves directly with *the physical constitution of the sun*, and with the periodical greater or less prevalence of *spots on his surface*; the maxima of the amount of fluctuation correspond to the maxima of the spots, and these, again, with those of the exhibitions of the aurora borealis, which appears also to be subject to the same law of periodicity—a law which, as it does not agree with any of the otherwise known solar, lunar, or planetary periods, may be considered, so to speak, personal to the sun himself.

Such is a brief summary of the results obtained at the colonial observatories up to the time of the report of the joint committee. We will now attempt a brief review of what has since been accomplished at the observatories of Kew and Greenwich, for the materials of which we are mainly indebted to the luminous memoirs of Sir Edward Sabine, the astronomer royal, and Dr. Balfour Stewart, which appear in the "Transactions and Proceedings of the Royal Society."

227. Kew.—The method of investigating the laws of the larger magnetic disturbances of the declination at the Kew Observatory is thus explained by Sir Edward Sabine. The photographs of the self-recording declinometer furnish a continuous record of the variations which take place in the declination magnet, and admit of an exact measurement in the two relations of *time* and of the amount of departure from a zero

line. From this automatic record the direction of the magnet is measured at twenty-four equal intervals of time in every solar day, which thus become the equivalents of the "hourly observations" of the magnetometers in use at the colonial observatories. These measures or hourly directions of the magnet are entered in monthly tables, having the days of the month in successive horizontal lines, and the hours of the day in vertical columns. The "means" of the entries in each vertical column indicate the mean direction of the magnet at the different hours of the month to which the table belongs, and have received the name of *first normals*. On inspecting each monthly table, it is at once seen that a considerable portion of the entries in the several columns differ considerably from their respective means or first normals, and must be regarded as *disturbed* observations. The laws of their relative frequency and amount of disturbance in different years, months, and hours are then sought out by separating for that purpose a sufficient body of the most disturbed observations, computing the amount of departure in each case from the normal of the same month and hour, and arranging the amounts in annual, monthly, and hourly tables. In making these computations, the first normals require to be themselves corrected, by the omission in each vertical column of the entries noted as "disturbed," and by taking fresh means, representing the normals of each month and hour after this omission, and therefore uninfluenced by the larger disturbances. These new means have received the name of *final normals*, and may be defined as being "the mean direction of the magnet in every month and every hour, after the omission from the record of every entry which differed from the mean a certain amount either in excess or in defect."

In a scale on which the changes of direction of the declination magnet are recorded in the Kew photographs, one inch of space is equivalent to 22.04' of arc. On a general view and consideration of the photographs during 1858-'59, 0.15 inch, or 3.31' of arc, appeared to be a suitable amount for the separating value (the measure of a large disturbance) to be adopted at that station; consequently every tabulated value which differed 3.31', or more either in excess or defect from the *final normal* of the same month and hour, was regarded as one of the larger disturbances, and separated accordingly.

The number of "disturbed" observations in the two years was 2,424, viz, 1,211 in 1858, and 1,213 in 1859, being between one-seventh and one-eighth of the whole body of hourly directions tabulated from the photographs, of which the number was 17,319. The aggregate value of disturbance in the 2,424 observations was 14,901 minutes of arc, of which 7,207 minutes were deflections of the north end of the magnet to the west, and 7,694 minutes to the east.

The number of disturbed observations, as well as their aggregate values, approximated very closely in each of the two years, 1859 being in slight excess. The decennial period of the *magnetic storms* indicated

by the observations at the British colonial observatories between 1840 and 1850, had led to the anticipation that the next epoch of the maxima of the cycle might take place in the year 1858-'59. The nearly equal proportions in which the number and aggregate values of the larger disturbances took place in 1858-'59, are so far in accordance with this view.

228. Laws of the westerly and easterly deflection at Kew.—The westerly and easterly deflections in the British Islands, as represented by the automatic records at Kew, are obviously governed, as in all other parts of the globe where the phenomena have been analyzed, by distinct laws.

The *westerly* deflections have their chief prevalence from 5 a. m. to 5 p. m., or during the hours of the day; the easterly deflections, on the other hand, chiefly prevail during the hours of the night, the ratios being above unity from 7 p. m. to 3 a. m., and below unity at all other hours. The *easterly* deflections have one decided maximum, viz, at 11 p. m., towards which they steadily and continuously progress from 5 p. m., and from which they as steadily and continuously recede until 5 a. m. the following morning. The *westerly* deflections appear to have two epochs of maximum, one from 6 to 8 a. m., the other about 3 p. m., progressing regularly towards the first named from 3 a. m., and receding from it to 9 a. m. At 9, 10, and 11 a. m. the ratios remain almost sensibly the same, but towards noon they begin to increase afresh, and continue to do so progressively to the second maximum at 3 p. m., from which hour they progressively decrease to 7 p. m. Those ratios which are less than unity, viz, those of the westerly deflections from 6 p. m. to 4 a. m., and of the easterly deflections from 4 a. m. to 6 p. m., do not in either case exhibit the same decided tendency to one or two well-marked *minima*, as the ratios which are above unity do in both cases toward their *maxima*.

229. Magnetic storms.—On comparing the phenomena observed at Hobarton, in Tasmania, with those observed at Kew, the laws of the magnetic storms experienced at both stations exhibit a resemblance not only general, but extending to such minute particulars that it is impossible to resist the impression that the accordance is not accidental. The disturbing effects due to magnetic storms are, however, somewhat greater at Kew than at Hobarton.

The first reference of magnetic storms to the sun as their primary cause was soon followed by a far more striking presumptive evidence of the same by the further discovery of the existence of a periodical variation in the frequency of the occurrence and amount of aggregate effects of the magnetic storms corresponding in period and coincident in epoch of maximum and minimum with the decennial variation in the frequency and amount of the spots in the sun's disc derived by Schwabe from his own systematic observations, commenced in 1826, and continued thenceforward.

The decennial variations of the magnetic storms are based on the obser-

vations of the four widely distributed colonial observatories, and are concurred in by all. This remarkable correspondence between the magnetic storms and physical changes in the sun's photosphere, of such enormous magnitude as to be visible from the earth even by the unassisted eyes, must be held to terminate altogether any hypothesis which would assign to the cause of the magnetic disturbances a local origin on the surface, or in the atmosphere of our globe, or even in terrestrial magnetism itself, and to refer them, as cosmical phenomena, to direct solar influence.

Two magnificent auroral displays, the first commencing on the evening of August 28, and the second on the early morning of September 2, 1859, were observed nearly at the same time throughout the globe, and at the time of their occurrence a large spot was seen on the disc of the sun. Magnetic disturbances of great violence occurred simultaneously with these displays. Telegraphic communication was in many instances interrupted, and in some cases the current produced in the wires was so powerful that it was used instead of the ordinary current, the batteries being cut off, and the wires connected with the earth.

As regards the magnetic needle, the average effect of the disturbances was to increase the declination and to diminish the horizontal and vertical components of the earth's magnetic force.

On the forenoon of September 1, 1859, at 15 minutes past 11 o'clock, a third, but minor, disturbance took place, which affected the magnetograph at Kew simultaneously with the breaking out near a spot in the sun's disk of a bright star, which was observed independently by Mr. Carrington and Mr. Hodgson.

A study of the curves furnished by the magnetographs during this great storm seems to throw light upon the connection which subsists between magnetic disturbances, earth currents, and auroral displays. These curves show that at the commencement of the disturbance the horizontal and vertical components of the earth's force remain depressed below their normal value for at least seven hours. The curves for this portion of time have also a peculiar *serrated* appearance, as if in the great disturbance, whose period was seven hours, there were superimposed smaller waves, whose period might perhaps be only a few minutes, or even less.

Referring to this serrated appearance, Balfour Stewart suggests two hypotheses which may be entertained regarding them, viz, (1) they may be conceived to represent small and rapid changes in the intensity of the whole disturbing force which acts upon the magnet; (2) the peaks and hollows may be supposed due to the direct action of *earth currents* upon the magnets. This second hypothesis he regards as untenable, because the peaks and hollows of the disturbance curves do not accord with the directions of the earth currents, as observed by Mr. Walker in the telegraphic lines between Margate and Ramsgate, and between Ramsgate and Ashford. Mr. Stewart considers earth currents to be

probably induced currents due to sudden and rapid changes in the magnetism of the earth. The peaks and hollows he considers as representing small and rapid changes in the intensity of the whole disturbing force which acts upon the magnet, and these peaks and hollows, he thinks, may be made use of to analyze the forces concerned in producing disturbances.

230. Lunar variation.—M. Kreil first suggested the existence of a lunar diurnal variation of declination, from observations made at Milan and Prague. The character and amount of the moon's influence on each of the magnetic elements has been determined at Toronto, St. Helena, and Hobarton. All the observations present the same general characters, viz, a double progression in the twenty-four hours, having epochs of maximum and minimum symmetrically disposed. In character, therefore, it differs from what might be expected to take place if the moon were possessed of *inherent* magnetism. On the other hand, it is believed that the amount of the variation far exceeds what can be imagined to proceed from the earth's inductive influence reflected from the moon.

The aspect of the lunar diurnal variation at Kew and Hobarton presents features of great simplicity as well as accord. The form at both stations is a division of the 24 lunar hours into four equal or nearly equal portions, in which the magnet is attracted alternately to the east and to the west of its mean position, which is passed through four times in the progress of the magnet towards two extreme easterly and two westerly deflections. The easterly extremes are about twelve hours apart, and the westerly the same. This appears to be the general form of the lunar diurnal variation of the declination at all the stations at which it has been examined. It is also that of the corresponding variations of the dip and total force.

The lunar times when the moon's influence produces no deflection (or the times when the variation is zero) are four, and are nearly the same at Kew and at Hobarton, two of them being a little more than an hour before the moon's passage of the meridian, both at her upper and lower culminations, and the other two intermediate. So far, the two stations are alike; but in regard to the direction towards which the magnet is deflected (if, in conformity with general usage, we speak in both hemispheres of the north end of the magnet), the variation becomes west at Kew when it becomes east at Hobarton, and *vice versâ* the phases while agreeing in hours at the two stations having throughout opposite signs.

Sir Edward Sabine, from a tabulation of the records derived from a seven years' series of photograms obtained at the Kew Observatory between January 1, 1858, and December 31, 1864, deduces the following fact connected with the lunar influence on the terrestrial magnetic influence, viz, a lunar diurnal variation, small in amount, but having peculiar and well-marked systematic characteristics, exists in each of the

magnetic elements, presenting a similarity and accordance which it is impossible to regard as accidental, with the results obtained at several other widely separated localities in the middle latitudes of both hemispheres, as, for example, at Hobarton, Toronto, Philadelphia, Pekin, and the Cape of Good Hope.

A magnetic variation shown to be thus obviously dependent upon the moon's position relatively to the terrestrial meridian, and agreeing in its principal features in such various localities, is urged by Sabine as being ascribable with great probability to the direct magnetic action of the moon, made sensible at the surface of the earth through the production of phenomena which, in the present state of our knowledge as regards the magnetism, both of the earth and of the moon, it is as yet difficult wholly to explain, but which are likely to lead to a considerable advance of our knowledge in both these respects.

231. Secular change and annual variation of the declination.—There is at Kew a variation in the declination having an annual period, and consisting of a semi-annual inequality with epochs coincident, or nearly so, with the sun's passage of the equator, the magnet being deflected towards the east when the sun is north, and towards the west when he is south of the equator.

The amount of semi-annual inequality averages $-28.95''$ in the weeks from March 21 to September 21, and $+29.9''$ in those from September to March. The whole amount of variation is therefore $58.86''$.

A comparison with the result of investigations of the corresponding phenomena at Hobarton, in the southern hemisphere, and at St. Helena in the equatorial zone, shows the existence of a semi-annual inequality, with epochs coinciding or nearly so with the equinoxes at both stations, the deflections being in the same directions as those at Kew, viz, to the east when the sun is north, and to the west when he is south of the equator. The amount of the annual variation thus produced is less at St. Helena than at either Kew or Hobarton, the semi-annual difference being about $7''$, and the annual variation $14''$.

It is remarked by Sabine that the difference in amount of deflection at the three stations may in part at least be occasioned by the difference in amount of the antagonistic force of the earth's magnetism tending to retain the magnet in its mean position in opposition to all disturbing causes. The antagonistic force, viz, the horizontal component of the earth's magnetic force, is approximately 5.6 (in British units) at St. Helena, 4.5 at Hobarton, and 3.8 at Kew.

On submitting the corresponding phenomena observed at the Cape of Good Hope to a similar investigation, an annual variation is shown of $0.8'$ (or $48''$), or a semi-annual inequality, averaging $24''$, to the east in the thirteen fortnights from March 26 to September 23, and $24''$ to the west in the thirteen fortnights from September 24 to March 25. This is in accordance with the conclusions at the other stations. The

antagonistic horizontal component of the earth's magnetism at the Cape is approximately 4.5.

The results of the monthly determinations of the dip and horizontal component of the magnetic force at Kew, as bearing upon the question of annual variation, may be stated as follows:

1. The dip is subject to an annual variation which, on the average of six years, amounts to 1.35', consisting of a semi-annual inequality, with epochs coinciding, or very nearly so, with the equinoxes, the mean dip being, on the average, 0.65' *lower* than its annual mean value in the six months from April to September, and 0.7' higher than its annual mean value in the six months from October to March.

2. That the horizontal force is subject to a semi-annual inequality, having the same epochs, being, on the average, .0013 *higher* than its annual mean in each of the six months from April to September, and .0013 *lower* than its annual mean in each of the six months from October to March.

3. That combining the results of the dip and horizontal force, the total terrestrial magnetic force is expressed in British units by 10.3002 as its mean value in the months from April to September, and by 10.30347 in the months from October to March, there being thus a difference of .00327, by which the intensity of the magnetic force of the earth is greater in the months when the sun is *south* than in the months when he is *north* of the equator.

232. The results of the monthly observations of dip and horizontal force, made at the Kew Observatory in the succeeding six years, viz, from April 1863 to March 1869 inclusive, have been reduced in a similar manner by Dr. Balfour Stewart.

First, as regards the dip.—From the six years' observations there is deduced the existence of a semi-annual inequality, in virtue of which the dip is, on an average, 0.27' lower in the six months from April to September, and 0.27' higher in the six months from October to March, than is due to its mean value. This result is in the same direction as that found by Sabine for the six years ending March, 1863, but is less in amount than the latter; that determined for the first six years exhibiting a range of 1.31', while that determined from the succeeding six years' period only exhibits a range of 0.54'. From the first six years a mean dip is deduced equal to $68^{\circ} 20.07'$, corresponding to middle epoch April 1, 1860; and from the latter six years a mean dip equal to $68^{\circ} 6.62'$, corresponding to middle epoch April 1, 1866; while the secular change deduced from the first series is 2', and that deduced from the last series is 1.92', the mean of the two values being 1.96'. Applying this mean value of the secular change to the mean result corresponding to the epoch April 1, 1860, in order to bring it to the epoch April 1, 1866, we obtain—

$$68^{\circ} 20.07' - 11.76' = 68^{\circ} 8.31';$$

whereas that deduced from the second series corresponding to this epoch

is $68^{\circ} 6.62'$; the former of these is $1.69'$ higher than the latter. Now, it was remarked by Sir Edward Sabine that—

The general effect of the disturbance of the inclination at Toronto is to *increase* what would otherwise be the amount of that element; and therefore, if the disturbances have a decennial period, the absolute values of the inclination, if observed with sufficient delicacy, ought to show in their annual means a corresponding decennial variation, of which the minimum should coincide with the year of minimum disturbance, and the maximum with the year of maximum disturbance.

At Toronto, where the true secular change is very small, the effect of this superimposed variation is very visible, so that the yearly values of the inclination appear to increase up to the period of maximum disturbance, and to decrease after it. At Kew the general effect of disturbances is probably the same as at Toronto; that is to say, tending to increase the inclination. The joint effect of the secular change and the superimposed variation might be expected to appear in a diminution of the yearly secular change for those years during which the disturbances are increasing from their minimum to their maximum value, and in an increase of the yearly secular change for those years during which the disturbances are decreasing from their maximum to their minimum. Dr. Stewart represents graphically a curve showing the law of diminution of the dip at Kew, due to the conjoint action of those two causes, and shows that the observations agree with it as a matter of fact; that in the Kew observations the secular change is *less* than the mean during periods of increasing disturbance, and *greater* than the mean when the disturbances are decreasing. It appears that the Kew observations present a peculiarity similar to those at Toronto, so that the difference of $1.69'$ between the two sets of observations may probably be accounted for by this cause.

Second, as regards horizontal force.—The observations were made with the “Kew unifilar,” and reduced precisely after the manner of those described by Sabine in his analysis of the first six yearly series.

The absolute values of the horizontal force corresponding to the beginning of October in each of the six years, and the secular change in each year, are as follows:

From April 1863 to March 1864.....	3.8216	} Secular change + 0.0068
From April 1864 to March 1865.....	3.824	
From April 1865 to March 1866.....	3.8306	} Secular change + 0.0022
From April 1866 to March 1867.....	3.8391	
From April 1867 to March 1868.....	3.8467	} Secular change + 0.0076
From April 1868 to March 1869.....	3.8493	
Mean of the six years corresponding to middle epoch April 1, 1866	} 3.8310	{ with a mean annual secular increase of + 0.0055.
Mean of the six years corresponding to middle epoch April 1, 1860.		
	} 3.8034	{ with a mean annual secular increase of + 0.0053.
Mean of the two 0.0054.		

Applying this mean value of the secular change to the mean result corresponding to epoch April 1, 1860, we obtain $3.8034 + (0.0054 \times 6) = 3.8358$, a value which agrees as nearly as possible with that deduced

from the second series, and corresponding to the same epoch, which, as seen above, is 3.8360. The coincidence of these two values naturally leads to the conclusion "that the secular change of the horizontal force does not present the same peculiarity as that observed in the case of the dip."

Third, as regards total force.—The mean of the April to September values of the horizontal component of the force in the last six years is 3.8346, corresponding in epoch to January 1, 1866; and the mean of the April to September values of the dip, in the same six years, is $68^{\circ} 6.83'$. It is found also that the mean of the October to March values is for the horizontal force 3.8372, and for the dip $68^{\circ} 6.41'$, corresponding to epoch July 1, 1866. These may be reduced to a common epoch by applying to the former dip the correction $-0.96'$; this being the proportional secular change, as shown by these six years, necessary to reduce the former epoch to the latter, the former dip will therefore become $68^{\circ} 6.83' - 0.96' = 68^{\circ} 5.87'$.

Reducing in the same way the horizontal force, we have $3.8346 + 0.00275 = 3.83735$. The values thus become as follows:

	Horizontal force.	Dip.
From the April to September observations (reduced to epoch July 1, 1860)	3.83735	$68^{\circ} 5.87'$
From the October to March observations (reduced to the same epoch)	3.83720	$68^{\circ} 6.41'$

The total force derived from the first series will therefore be 10.28717, and that derived from the second series 10.29080, showing thus a difference of 0.00363 in British units as the measure of the greater intensity of the magnetic force in the October to March period than in the April to September period. This is in the same direction, and very nearly of the same amount, as that determined by Sabine from the first six years; which exhibited a similar difference of 0.0037 in British units.

It is thus found that the two series agree in showing nearly the same semi-annual variation for the total force, whilst the first period exhibits the greatest semi-annual variation of the dip. It must be borne in mind, however, that the two series bear a different relation to the disturbance period, the maximum disturbances occurring about the middle of the first series, and the minimum near the middle of the second.

233. The variations of the magnetic dip in London.—The secular changes which have taken place in the magnetic dip in London during the thirty-nine years between 1821 and 1860 have been discussed by General Sabine. The period is divided into four epochs, viz, epoch of 1821, epoch of 1838, epoch of 1854, and epoch of 1859.

First epoch of 1821.—The experiments were made in the Regent's Park. The circle employed was $11\frac{1}{2}$ inches in diameter, made by Nairne, and the needle by Dollond. The mean of the experiments gave as the dip for this epoch $70^{\circ} 02.9'$.

Second epoch of 1838.—The experiments were made in the Regent's

Park, in Kew Garden, and in Westbourne Green; the instruments were made by Robinson, Gambey, and Jordan. The mean of thirteen determinations gave as the dip for this epoch $69^{\circ} 23.9'$.

Third epoch of 1854.—The experiments were made in the Regent's Park and at Kew with two inclinometers by Barrow, fitted with verniers and microscopes, and each having two needles. The mean of eighteen determinations gave as the dip for this epoch $68^{\circ} 31.13' N$.

Fourth epoch of 1859.—The experiments were made in the Regent's Park and at Kew, on 121 days between November, 1857, and December, 1860, during which period 282 observations were made. There were employed in these determinations twelve circles and twenty-four needles, the circles being 6 inches in diameter, fitted with verniers and microscopes, and the needles $3\frac{1}{2}$ inches in length. Every determination was complete in the eight different positions of the circle and needle. The results in each year are reduced to the 1st of July in the same year, employing a proportional part of an annual secular change of $-2.6'$. Those which were obtained in the four winter months of November, December, January, and February have also received a correction of $-0.8'$; and those obtained in the summer months, May, June, July, and August, a correction of $+0.8'$ in compensation for annual variation.

The following are the results:

	Dip.
July 1, 1858, mean of 115 observations	$68^{\circ} 23.2'$
July 1, 1859, mean of 96 observations	$68^{\circ} 21.5'$
July 1, 1860, mean of 71 observations	$68^{\circ} 19.8'$

Corrections for annual variation.—The observations both at Toronto and at Kew concur in showing that after the elimination of the effects of secular change the north dip is somewhat greater ($1.6'$) in the winter than in the summer. Of this number one-half ($0.8'$) is to be applied with the sign $-$ to the results in the winter months, and with the sign $+$ to the results in the summer months. The dip therefore at the several epochs, when finally corrected, stands thus:

1821.65	$70^{\circ} 03.4' N$	(1)
1838.30	$69^{\circ} 17.3'$	(2)
1854.65	$68^{\circ} 31.6'$	(3)
1859.5	$68^{\circ} 21.5'$	(4)

The rate of diminution of the dip in London in the last forty years does not appear to differ materially from the mean rate in the preceding 100 years. The experiments of Mr. George Graham between March and May, 1723, give a mean dip of "nearly" $74^{\circ} 40'$. Comparing this with $69^{\circ} 11.95'$ in 1840, we have a difference of $5^{\circ} 28.1'$ in 116.7 years, equivalent to a uniform diminution of $2.8'$ annually.

CHAPTER IX.

REVIEW OF MAGNETIC THEORY.

General principles—First views of terrestrial magnetism—Hypothesis of Halley—Speculations of Euler—Theoretical speculations of Hanstein—Grover's magnetic orbit—Theory of Barlow—Hypothesis of Biot—Theory of Gauss—Electro-magnetic theory—Theoretical views and recent discoveries of Faraday—Theory of ordinary magnetic action.

234. One of the great objects of physical science is to trace the relations and determine the laws of sequence in any observed series of natural phenomena, the study of nature being "the study of facts, not of causes"; it is this which characterizes the learning of the great founder of the inductive philosophy, and which essentially separates it from the conjectural philosophy of remote ages, the object of which was the study of causes rather than of facts. By the term "theory," as applied in modern science, we are to understand an intelligibly connected body of facts, all referable to one or more general principles. With respect to the hidden or efficient cause of the phenomena observed, we have really no substantial knowledge of it whatever. That all bodies tend to the center of the earth, and masses of matter toward each other, are universal facts; and upon these is based the whole theory of gravitation, and a lucid explanation of the system of the world. In the midst of this knowledge, however, we are most profoundly ignorant of the nature of the agency by which matter gravitates; and to speculate concerning it through the instrumentality of fiction would be only to wander in a labyrinth of conjecture. What we call "an explanation of observed phenomena" is a clear apprehension of all the dependencies in a great chain of sequence. Take, for example, the question of the rise of water in a pump before the discovery of Toricelli; here we had two facts before us: the elevation of the fluid full thirty feet above its level, and the production of empty space by the motion of the piston of the pump; still the vacuum and the rise of the fluid had no apparent dependence on each other. The assumption by the ancient philosophers that the elevation of the fluid arose from the circumstance that nature abhorred a vacuum, was, in fact, no adequate intermediate link; it explained nothing. Directly, however, it was proved by the experiment of Toricelli that the atmosphere pressed upon bodies with a force equal to at least 14 pounds on the square inch, then the cause of the rise of the fluid was instantly apparent, and the phenomena were explained. In the construction, therefore, of any theory, it is essential that the basis of it be some principle reducible to a fact; and, next, that the fact be universal, that is, without exception. Directly we refer the phenomena to any fictitious principle not reducible to a fact, we have no longer a

theory; we have only at the best a conjectural hypothesis; in short, we substitute something which has no demonstrable existence for that which may be: in this case, we only require that what we assume is possible. An hypothesis of this kind is still not without its uses; and it is theoretically admissible so long as it runs parallel with the facts observed.

Magnetic theory, embarrassed by the complicated and mysterious character of the attendant phenomena, has hitherto made but comparatively little progress toward perfection; so that we are unable, as in gravitation, to refer the facts to one ultimate and universal elementary principle; hence, almost every speculation relative to the phenomena of magnetism partakes more or less of the nature of an hypothetical assumption not based on any recognized fact.

235. *First views of terrestrial magnetism.*—The philosophers of the sixteenth century, not having any definite notion of the phenomena of the compass-needle, conceived it to be influenced by some mysterious point of force existing in the regions of space. Descartes and others conceived it to be under the dominion of vast magnetic rocks. The discovery of the magnetic inclination by Norman, in 1580, however, clearly proved that the cause of the directive position of the magnetic needle was to be sought for in the general mass of the earth; whilst Gilbert, in 1590, taking a bolder view of this great physical question, conceived the terrestrial sphere to be in itself a vast magnet, endowed with a permanent polarity, and hence approaching the general condition of an ordinary lodestone. Gilbert supposed, however, that the solid parts only of the earth were magnetic, not the water or other fluids; hence arose changes in the direction of the needle, which, whilst it assumed a given position, in obedience to the laws of common magnets, would at the same time be more or less drawn toward the land, and be influenced by it in various ways.

Bond, in 1673, endeavored to calculate and explain the phenomena of the magnetic needle, on the hypothesis of the earth being a great magnet, and assumed the existence of two terrestrial magnetic poles, and a magnetic axis inclined to the axis of rotation, and passing through the center of the earth; hence the magnetic poles and the true poles could not on this hypothesis coincide. With a view of explaining the great secular changes in the declination, the magnetic poles were supposed to have a slow movement of revolution about the poles of the earth.

236. *Hypothesis of Halley.*—It is to the celebrated Halley that we owe the first great attempt to bring the complex phenomena of the horizontal needle under the dominion of a more comprehensive theory, which, although it may appear at first to be of a somewhat rude and improbable character, still affords a fair field for the application of exact reasoning, and a means of comparing facts; indeed, it is but justice to this truly great man to observe, that he never pretended to more than an attempt

to throw some light upon "the abstruse mystery of the variation," and lead philosophers to apply themselves more forcibly to so important a subject. Were the variation always relative to two fixed points or poles near the poles of rotation, the magnetic axis passing through the center of the earth, then it should be always the same for each place, and the lines of no variation would be meridian lines, passing through the magnetic and real poles of the earth; but the lines of no variation are not meridian lines, but curves of a somewhat inexplicable course. Halley, therefore, foreseeing this difficulty, assumed the existence of at least four poles, to which the variation had reference, two in the northern and two in the southern hemisphere; but since the observed phenomena evidently indicate a constant change of place in the relative position of these poles, he further supposes that the whole "magnetical system of the globe has one or perhaps more motions, the effects of which extend from pole to pole." To render this magnetical movement intelligible, he supposes a great portion of the interior of the earth to move within the external crust; and to admit of this motion he imagines this interior portion to be detached and separated from the surface by an intervening fluid medium, so that, according to this, the terrestrial mass is a sort of double lodestone, consisting of an interior magnetic spherical nucleus, surrounded by an external and spherical magnetic shell, the magnetic axis of each passing through the center of the whole globe of the earth; the nucleus is supposed to have its center of gravity fixed in the common center of the general spherical mass, and to partake of the diurnal rotation about the same axis. By further supposing that the rotary movement of the surface or external shell is rather more rapid than that of the interior globe, by some extremely small quantity, then, as is evident, the poles of the interior magnet will be continually shifting their places in respect of the poles of the outer magnetic shell, being at every revolution left, as it were, a little in the rear, and consequently moving apparently westward. Halley supposes the difference of velocity to be so extremely little as to be scarcely appreciable upon 365 revolutions, and only to assume a sensible form by the operation of a great period of time. Under this condition, then, if we conceive the exterior shell to be a magnet, having its poles fixed, and at a given distance from the poles of rotation, and if the internal globe be also a magnet, having its poles fixed in two other places, distant also from the axis of rotation, and that these last poles are continually shifting their places in respect of the exterior poles, we may then, he thinks, give a reasonable account of the four magnetic poles of the earth, considered as a magnet, and the several phenomena of the variation of the horizontal needle. By the gradual translation of the poles of the internal globe, the direction of the needle is variously influenced, according to the directive power of each pole; hence there will be a period of revolution, after which the variations will return again as before. If they should not, then it may be

inferred that there exist internal spherical shells, having a common nucleus, and consequently producing more magnetic poles, all these concentric magnetic spheres being separated by fluid media; and this he thinks a possible constitution of the interior of our planet, which, for anything we know to the contrary, may, through the operation of the fluid media, be a source of existence to organized beings. In this hypothesis all those parts of the earth nearest either of the poles will for the time be governed more or less by the influence of that pole; thus, taking the nearest pole to Britain as being in the meridian of the Land's End, and about 7° from the true north pole, this pole will govern Europe, Tartary, and the North Sea. All places to the east of this meridian will have a westerly variation; all places west of it, an easterly variation, until we approach the influence of the other pole, in North America, supposed to be on the meridian of California. The separate and combined influences of all the four poles in different zones of the earth produce the great differences observed in the variation of the needle.

This hypothesis of Halley, although far within the region of mere conjecture, and not at first view sanctioned by any high degree of probability, must still be considered as a valuable step in the progress of magnetic theory, and well calculated as a stepping-stone to more perfect views of the magnetism of the earth.

237. *Speculations of Euler.*—Euler, who investigated this subject in 1757, with his accustomed ability, does not think, in considering the earth as a magnet, that it is requisite to assume the existence of more than two magnetic poles, provided their just place be assigned. According to his view, we have yet to consider the case of two magnetic poles not precisely opposite each other, or, which comes to the same thing, in which the magnetic axis does not pass through the center of the earth. Now, in this case, Euler endeavors to show that the lines of no declination may actually assume a direction similar to that which from observation we find they do assume; and that it is even possible to assign to the two poles such proportions as to produce lines of variation similar to those isogonal lines which at first appear so unaccountable. Having fixed the two poles, the determination of the direction of these lines becomes a problem in geometry.

238. *Theory of Hanstein.*—Theoretical views of terrestrial magnetism do not appear to have greatly advanced beyond the condition in which Halley left them until 1811, when the Royal Danish Academy proposed the variation of the needle as a prize question; then it was that M. Hanstein undertook a re-examination of the whole subject, with a view to determine whether two magnetic poles, revolving round the pole of the earth in indefinite periods, as maintained by Euler, would explain the phenomena; or whether four poles, as assigned by Halley, were requisite; or finally, whether the motion of magnetic polar points about

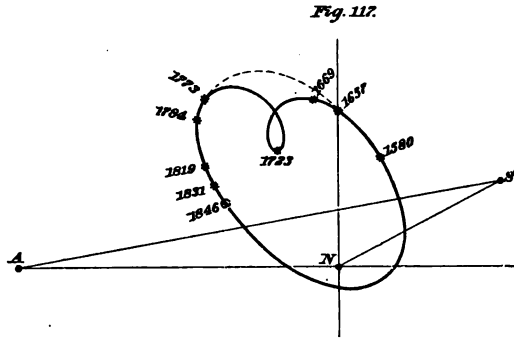
the poles of the earth be in any way competent to represent the observed phenomena at all. We have already adverted to the extraordinary and elaborate magnetic charts of this unwearied philosopher, with their marked systems of isogonal lines, loops, ovals, and other intricate convolutions, and which it would seem are all sweeping westward, each in separate progression, and each assuming some new modification of flexure. So completely has the question been worked out that by the means of these charts we obtain a faint glimpse of the progressive state of magnetic declination for two centuries, viz, from 1600 to 1800. The results of the investigation confirm, according to Hanstein, the existence of four poles, as imagined by Halley. These four poles, however, are of unequal force, and are all supposed to be continually shifting their places; each has a separate independent movement and period. The present places of these poles, as assigned by Hanstein, we have already given; they are all supposed to have a regular oblique-circular motion about the poles of the earth—the two north poles from west to east; the two south poles from east to west; and in the following periods: The strongest north pole in 1,740 years; the weaker in 860 years; the strongest south pole in 4,609 years; the weaker in 1,304 years. Upon these data he assigns the position of these poles for the last half-century.*

239. Grover's magnetic orbit.—Much valuable information relative to this interesting speculation has been afforded by Grover. By a careful and laborious examination of authentic observations, he endeavors to show that "the movement of the magnetic pole governing Europe is capable of recognition, that it possesses an orbital character of which the general features can be distinctly traced." An horizontal action upon the needle is also inferred from these observations, depending on the isodynamic poles, by which he endeavors to explain the configuration of the isogonic lines. The magnetic orbit, as traced from observations on the magnetic needle in London, Paris, and St. Petersburg, ap-

* By a curious coincidence, these periods involve a number, 432, sacred with the Indians, Babylonians, Greeks, and Egyptians, as being dependent on great combinations of natural events; thus the periods 860, 1,304, 1,740, and 4,609 become, by a slight modification, 864, 1,296, 1,728, 4,320, which are not inadmissible, considering the complicated nature of the observations from which the first numbers are derived. Now these numbers are each equal to 432 multiplied by 2, 3, 4, and 10 successively. According to the Brahmin mythology, the world is divided into four periods, the first being 432,000 years, the second $2 \times 432,000$, the third $3 \times 432,000$, the fourth $10 \times 432,000$ years. It is also, according to Hanstein, not unworthy of remark that the sun's mean distance from the earth is 432 half-radii of the sun; the moon's mean distance 432 half-radii of the moon; but what is more especially striking is the circumstance that the number $25,920 = 432 \times 60$ is the smallest number divisible at once by all the four periods, and hence the shortest time in which the four poles can accomplish a cycle. Now, this time coincides exactly with the period in which the precessions of the equinoxes complete their circle—certainly a curious and remarkable series of coincidences.

pears to be of the form given in the annexed Fig. 117. In this figure N is the true north pole in the middle of a section of the northern hemisphere, and the irregular elliptical curve the path of the pole so far as hitherto observed.

In this curve the author has localized eight assigned positions for the magnetic pole, from observations between the years 1580 and 1846. The points A and S represent the positions of the isodynamic poles, or points to which the isodynamic lines converge, one in Siberia, the other in America, and supposed to influence the position of the needle. In tracing the elements out of which this orbit is constructed, peculiarities present themselves which throw much light on the whole magnetic system; for example, a certain acceleration and retardation of the motion, and the opposite bias of the two isodynamic hemispheres. By means of a critical examination of all the phenomena of this determined orbit, the author deduces some very general and curious facts bearing on the development of the magnetic lines, with their ovals, loops, and apparently inexplicable curvatures. The ovals he considers as temporary creations arising out of the peculiar position of the moving magnetic pole in relation to the two isodynamic poles A, S, by which a bias is given to the needles of a whole district.

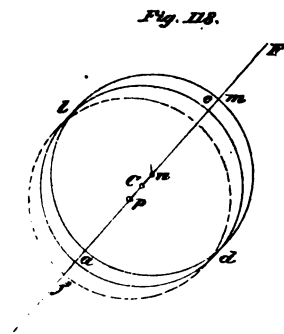


of the moving magnetic pole in relation to the two isodynamic poles A, S, by which a bias is given to the needles of a whole district.

240. Theory of Barlow.—Professor Barlow, following up the construction of more perfect magnetic charts, is led to conclude that these charts present such a configuration of the magnetic lines as cannot be referred to any possible position of four or more magnetic poles; but conceives that each place has its own relative pole and polar revolution governed by some unknown cause. This theory is so general that it must be conceived to set aside altogether the idea of any particular pole or point toward which the magnetic needle becomes directed, and consequently all idea of a single magnetic axis; it hence leaves the law of the changes in the direction of the needle undetermined. The fundamental principle on which this theory rests assumes the magnetic condition of the earth to be of that peculiar form observed in the passive or temporary magnetic state of a soft iron ball or shell, and in which the poles or centers of action are always coincident with the center of attraction of the surface, which is not the case in permanently magnetized bodies. In these the centers of attraction are always at their poles. Professor Barlow having, as we have already seen, found the entire effect of a soft iron globe or shell to reside near the surface, proceeded to investigate a formula for representing the influence of these bodies on the compass-needle placed about them in different positions. Assum-

ing, upon the generally received hypothesis, that magnetic phenomena depend on two opposite fluids or forces, repulsive of themselves, but attractive of each other, and commonly existing in a greater or less degree of combination, we may suppose the action of the earth on spheres of soft iron to take place on every particle of the mass in isoclinical lines parallel to each other, and may further suppose that every particle of the iron is at the same distance from the center of force as referred to the mass of the earth; in which case we may consider the effect upon each particle to be the same.

As this question is important in a theoretical view, we will take Professor Barlow's illustration of this probable



magnetic condition of a soft iron ball or shell. Let $a b c d$ (Fig. 118) be a neutral soft iron sphere. Suppose $F C f$ to be the direction of the dipping-needle, and F the center of terrestrial magnetic force at an indefinite distance; then by the operation of this force upon each particle, in the way just stated, the two magnetic fluids or forces resident in a combined state in the shell or globe $a b c d$ become separated, and may be supposed to form two spherical layers: one, $f b d$, whose center is p ; and another, $m b d$, whose center is n ; the distance of these centers p, n from each other depending on the susceptibility of the iron and other contingencies. In computing the action of an iron sphere in this state upon a distant magnetic particle, we may refer the action to those two centers p, n , according to any assumed law of force. Professor Barlow supposes the force to be in the inverse duplicate ratio of the distance. This view differs from others of a similar kind in this, that the action or displacement of the fluids is referred to each particle, instead of the fluids being separated and accumulated in distinct poles; and also in the great fact that the displacement is confined to the surface, and not, as Coulomb supposed, referable to the mass. The centers of action p, n , therefore, may become indefinitely near each other in the common center of attraction of the surface, which is coincident with the center of attraction of the mass only in spherical bodies, but on no others. Now by referring the earth's magnetism to an existing magnetic condition such as this, Professor Barlow finds that he is enabled to apply the analytical expressions he had previously deduced for representing the influence of an iron sphere on the compass to the phenomena of terrestrial magnetism; his general deductions being that the earth is not a permanent magnet, but owes its magnetic state entirely to induction; and that its action may be referred to two poles indefinitely near each other in the common center of attraction of the surface; that is also of the mass of the earth. The latent magnetism of the sphere has in this case a mere condition of polarity. From whence this induction proceeds he does not pretend to determine. The

illustrious Gableo had an idea that a magnetic agency existed in some points of space, which led him to ascribe the parallel direction of the earth's axis to a magnetic point of attraction in the distant heavens.

241. Hypothesis of Biot.—Biot, so long since as the year 1805, not finding it possible to reconcile observations on the variation and dip of the needle with the existence of two poles or centers of force near the terrestrial surface, thought of treating this problem under the condition that those centers were indeterminate, and then, by a comparison of the general analytical result with further observations endeavor, to arrive at the precise position of these poles. Now, it is not unworthy of remark as being very confirmatory of Barlow's views that the nearer the poles were taken toward each other the nearer the computed and observed results were found to agree; until at length, by taking them indefinitely near each other in the center of the earth, the computed and observed results in many cases completely coincided. In this investigation M. Biot assumes two points in a given terrestrial magnetic axis, by one of which the needle is attracted, by the other repelled; and then investigates a formula for representing the dip and declination of the magnetic needle in any part of the earth in terms of an indeterminate distance between these points.

242. Theory of Gauss.—This accomplished philosopher, whose magnetic researches have become in recent periods the wonder and admiration of Europe, assumes the terrestrial magnetic force to be the collective effect of the magnetism of the mass, and is led to consider the term pole as a very arbitrary assumption; no number of definite points, be they 2 or 4, or even more, will explain the phenomena according to the laws of common magnetism. In the most simple meaning of the term pole, Gauss considers that there are only two, one in each hemisphere. If there were four, we should have necessarily three points of verticity in each hemisphere; that is to say, there would be a point between each two poles in which the needle would not obey the action of either exclusively, and would consequently be vertical; but such is not found to be the case. Gauss, starting from a great general principle, that magnetism is distributed through the mass of the earth in an unknown manner, has succeeded in obtaining, partly by theory and partly by adaption, a sort of empirical formula which represents in a wonderful way the many complicated phenomena of the magnetic lines, and has so far embodied our knowledge of these phenomena in a law mathematically expressed. Gauss's investigation depends on the development of a peculiar function much employed in physical astronomy, and which is obtained by summoning all the attractive and repulsive elements, each molecule being divided by its distance from the attracting or repelling point; what are termed the differential coefficients of this function express the resolved components of the total magnetic action. By this process it is demonstrated that, whatever be the law of magnetic distribution, the dip, horizontal direction, and intensity at any place on the earth may be com-

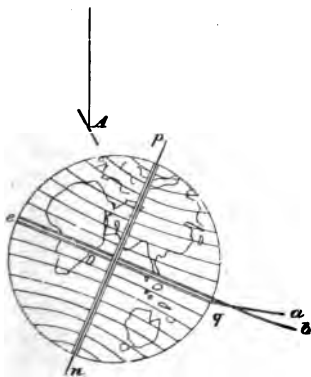
puted. Having exhibited his resulting formula in converging series, Gauss determines the declination, inclination, and intensity for ninety-one places on the earth's surface, and which are found to coincide with observation; one great feature, therefore, in this theory of terrestrial magnetism is, that the earth does not contain a single definite magnet, but irregularly-diffused magnetic elements, having collectively a distant resemblance to the condition of a common magnet. So that for magnetic poles we must substitute magnetic regions, over which a general magnetic influence obtains. Thus, instead of a Siberian pole, as determined by Haustein, we have a Siberian region, in which the isogonal lines may be conceived to converge without coming absolutely to a point.

243. *Electro-magnetic theory.*—The solution of the problem, whence the mass of the earth derives its magnetic state, is not in any way approached with so high a degree of probability as by the theory of electro-magnetic currents caused to traverse the earth's surface by some of those natural agencies so continually operating on it. We have seen that by heating one extremity of a metallic bar or rod, the opposite extremity being kept cool, so as to produce a disturbed equilibrium of temperature, electro-magnetic currents are produced, of such force as to turn the compass-needle at a large angle to its meridian. Sir David Brewster, so long since as the year 1821, observed a remarkable coincidence between the isothermal lines, or lines of equal heat, laid down by Humboldt, and the isogonal lines of Halley, and had deduced for our northern hemisphere two poles of greatest cold, both in the locality of Haustein's magnetic poles, viz, an American pole, lat. 73° north, long. 102° west; and an Asiatic pole, lat. 73° north, and long. 78° east. Sir David Brewster is led to conclude that two meridians of greatest heat, and two of greatest cold, are called into play, and was finally led to imagine that the magnetism of our globe depended in great measure on electro-, or rather thermo-magnetic currents. Taking into consideration the heated belt of the equatorial regions, and the mass of the polar ices on either side of it, we have, as observed by Dr. Traill, all the conditions of a vast thermo-magnetic machine. A great link in the chain, however, is still wanting; it is very difficult to say how or in what way these currents are caused to circulate about the mass of the earth: Grover, in his interesting little work on the magnetic orbit, already alluded to, has some interesting observations on this question. According to his view, the atmosphere is the immediate source of terrestrial magnetism, which contains within it isolated columns of conducting media; these surround the earth, and in such way that in 365 revolutions the sun generates in it an electro-magnetic circulation; thus the terrestrial surface becomes enveloped in a vast electro-magnetic spiral coil, and we who live on it become placed intermediate between the coil and the surface by those peculiar motions of the earth which arise from the yearly cycle finding its period at different hours of the day and on different meridians; such a change may take place in the precise position of this great atmos-

pheric coil from time to time as would correspond with the orbit of the magnetic revolution. The phenomena of periodical variations depend evidently on the action of heat and the position of the sun, and probably on resulting thermo-magnetic currents. Beyond this mere assumption, however, we have not any very secure basis for reasoning; the most admissible view of this kind of action, however, is the following: During the diurnal motion of the earth, its surface, especially about the tropics, is continually heated and cooled in successive points, and in an east and west direction; if we admit, as in Experiment 47, that thermo-magnetic currents become from this cause excited, and circulate in an east and west direction over the terrestrial surface, the result will be a magnetic development in direction north and south; hence there will be a magnetic development in the earth in a direction nearly parallel with its axis.

244. Barlow's electro-magnetic globe.—From no one has the preceding

Fig 119



electro-magnetic theory received so much substantial and fine experimental support as from the profound and great philosophical ingenuity of Professor Barlow. A hollow globe of wood, *p n*, Fig. 119, sixteen inches in diameter, had a groove, *e q*, cut round its equatorial part, to represent the equator, and also other grooves, in parallels of latitude distant $4\frac{1}{2}^\circ$ from each other. A deeper and wider groove, also, *p n*, was cut in it, extending from pole to pole in the line of a single meridian. Things being thus arranged, the middle portion of a copper wire one-tenth of an inch in

diameter, and ninety feet long, was applied to the equatorial groove, in a point opposite the line of the meridian *p n*, which, being bent each way, in the equator *e q*, to meet at the groove *p n*, was continued toward each pole by a continual coiling and turning into the parallels of latitude. Finally, the remaining portions of the wire were covered with insulating varnished silk thread, and passed through the meridian groove toward the equator, and the two extremities, *a b*, brought out for connection with the poles of a voltaic combination (40) (47). The whole was now covered with the pictured gores of a common globe, and in such way as to bring the poles of the electro-magnetic spiral as nearly as possible into the position of the observed terrestrial magnetic poles, viz, lat. 72° north, and lat. 73° south, and on the meridian corresponding with long. 76° west of Greenwich.

The globe being now conveniently placed under a delicately-suspended needle, *A*, Fig. 119, carefully neutralized in respect of the earth's action, electro-magnetic currents, were caused to circulate through the spiral beneath the paper surface. When the globe was so placed as to bring London into the zenith, the suspended needle took the inclination of the

dip, at that time 70° , and also the line of the variation, at that time about 24° west. On turning the globe round so as to bring other places of the same parallel under the needle A, the dip of 70° remained, but the line of declination changed its direction, becoming first zero and then increasing eastward, much in the same way as happens in the case of the horizontal needle. When the globe was turned so as to cause the pole to approach the zenith, the dip increased up to a point of verticity; and on turning it so as to bring the equator into the zenith, the suspended needle became horizontal. Continuing the motion so as to bring the south pole toward the zenith, the suspended needle inclined in the opposite way, thus representing on a small scale all the phenomena of the horizontal and inclined needles. Professor Barlow thinks that he has proved the existence of a force competent to produce all the phenomena of terrestrial magnetism without the aid of any body commonly called magnetic.

245. *Theory and recent discoveries of Faraday.*—This distinguished philosopher, with his accustomed vigor of intellect and practiced experimental hand, has not left the question of terrestrial magnetism unassisted by his immense labors. The general views which he is led to entertain upon points connected with the earth's magnetism may be thus stated: Space devoid of matter, as also material space, that is, space in which matter is found, may be taken as being traversed by lines of force, operating, as it were, immediately through it.* The condition of the space intercepted between the iron walls of the magnetic field, Fig. 59, may be taken as illustrative of this assumed physical condition of things. Now, although it may appear to many persons very difficult to conceive the existence of mere force independent of what we commonly call matter, yet we must recollect that, both in electricity and magnetism, it is with forces that we are principally concerned, and that, after all, it is far more difficult to conceive the existence of matter without properties of this kind than such properties without the matter; in fact, we recognize forces almost everywhere, but we recognize nowhere the ultimate atom of solidity of which matter is supposed to consist. All space, either vacant or occupied, presents for our consideration forces of various kinds, and the lines in which these forces are exerted. In viewing different substances in relation to lines of magnetic force, it is found that some bodies assume a position perpendicular to the direction of these lines; that is, they take an equatorial direction; others coincide in direction with the lines of force, and take an axial direction. Pure space, devoid of matter, is conceived to

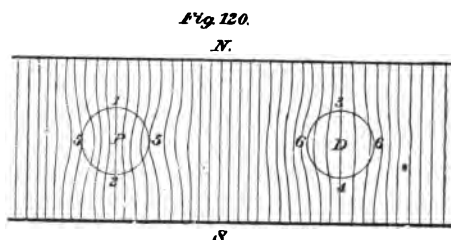
* Faraday defines a line of magnetic force as that line which a very small needle describes when it is so moved in either direction correspondent to its length that the needle is constantly a tangent to the line of motion, or that line along which, if a transverse wire be moved in either direction, there is no tendency to the formation of any current in the wire, whilst, if moved in any other direction, there is such a tendency. The direction of these lines about and between ordinary magnets is easily represented in a general manner by the use of iron filings.

have a magnetic relation of its own; that is to say, it permits lines of force to traverse it without in any way affecting them. The introduction of certain kinds of matter into space so occupied by force will, on the contrary, change the existing state of the lines by either increasing or decreasing the facility of transmission. Common matter, when referred to lines of magnetic force traversing pure space, may be considered as being either zero, or as producing no change, or as being on one side or the other of zero; that is, as producing opposite effects. Hence has arisen a classification of two kinds of magnetic substances, viz, those which point axially, and which have been termed paramagnetic substances, and those which point equatorially, termed diamagnetic. So that, taking the term "magnetic" in its most general sense, as applicable to all the phenomena, we have the following division:

Magnetic { Paramagnetic.
 Diamagnetic.

When paramagnetic or diamagnetic substances are introduced into the magnetic field, they either increase or decrease the degree in which the force is transmitted, and thus disturb the uniformity of the lines.

Paramagnetic substances, for example, concentrate the lines of force upon themselves, as represented by P in the annexed Fig. 120. Diamagnetic bodies, on the contrary, expand the lines of force, and cause them to open outward from themselves, as represented by D in Fig. 120.



Faraday calls this, for the moment, magnetic conduction. Paramagnetic bodies, when introduced into the magnetic field, always tend, from their power of concentration of force, from weaker to stronger places of magnetic action, and are urged in the axial line. Diamagnetic bodies, on the contrary, tend from stronger to weaker places, and are repulsed to the equatorial line. The force which thus urges bodies to the axial or equatorial lines is not a central force, but a force differing in character in the actual or radial directions. One may retain a very concise notion of this paramagnetic and diamagnetic relation by conceiving that if a liquid paramagnetic body were introduced into the field of force, it would become prolonged axially, and form a prolate spheroid; whilst a liquid diamagnetic body would become prolonged equatorially, and form an oblate spheroid.

246. Atmospheric magnetism.—By one of those happy trains of thought peculiar to great philosophical minds, Faraday conceived the idea of an atmospheric magnetism, and succeeded in proving that gaseous substances, when in the magnetic field, obeyed the same laws as all other matter. Thus oxygen gas, inclosed in a thin envelope, becomes drawn paramagnetically into the axial line, and is hence attracted by the magnet after the manner of iron, whilst olefant gas, for example, is repelled

diamagnetically into the equatorial line, after the manner of bismuth. The nitrogen of the air does not appear to be either paramagnetic or diamagnetic, but to constitute the zero place in the scale of different substances. In thus demonstrating the paramagnetic property of oxygen, we arrive at the very important fact that two-ninths of the atmosphere, by weight, consists of a substance magnetic in character, after the manner of iron, a substance liable to vast changes in its physical conditions of temperature and density, and by which its magnetic character would be liable to vary, independently of all consideration of magnetic force existing in the mass of our globe considered as a magnetic body *per se*.

The earth itself may be considered as a spherical mass, consisting of both paramagnetic and diamagnetic substances very irregularly disposed; it is nevertheless to be considered on the whole as a magnet, and as an original source of power. The magnetic force of this great system is disposed with a certain degree of regularity, so far as our opportunities of examining it extend, which is only on its surface. The lines of force which pass in or across this surface are made known to us, as respects direction and intensity, by means of small standard magnets. The average course, however, of these lines and their temporary variations, either in the space above or in the earth beneath, are but very obscurely indicated through the same means. Our observations, in fact, do not tell us whether the cause of the variations is above or below.

The lines of magnetic force issue from the earth in the northern and southern parts, with different but corresponding degrees of inclination, and incline to and coalesce with each other over the equatorial parts.

The lines of force which proceed from the earth into space most probably return to it again; but in their circuitous course may extend to a distance of many of its diameters, to tens of thousands of miles. Space, then, forms the great abyss into which such lines of force as we recognize by our instruments proceed. Between the earth and this space, however, there is the atmosphere; it is at the bottom of this we live, and in the substance of which we carry on all our inquiries. Now this medium is, as we have just seen, highly paramagnetic, and may evidently become changed in its magnetic relations by any change incidental to temperature or pressure. None of these changes can happen without affecting the magnetic force emanating from the earth, and causing variations at its surface both in intensity and direction.

Having examined a variety of circumstances affecting the magnetic condition of the atmosphere, and the probable way in which such changes would affect the magnetic needle, Faraday concludes that the magnet, as at present applied, is not always a perfect measure of the earth's magnetic force. The intensity, for example, in oxygen, of a given density, would be different from that in expanded oxygen, although the same amount of lines of force and magnetic energy were present in both cases. To understand this, we have to consider that a needle vibrates by gathering upon itself the lines of force P, Fig. 120, and which

otherwise would traverse the space about it. If the oxygen, therefore, be made dense, and a better conductor, then the magnet would carry on less of the force, and the oxygen more; it is therefore very important to know whether, when the magnet indicates an increased intensity, the intensity is due to the earth as a source of power, or to a change in the magnetic constitution of the surrounding space,* considering that the magnetic state of the earth may not change, whilst the oscillating needle, by the influence of the different conditions of day and night, or of summer and winter, may show a difference. So far the magnet, as at present applied, is not, according to this theory, a perfect measure of the terrestrial magnetic intensity. It is to the magnetic constitution and condition of the atmosphere, and the changes liable to be effected in it from changes in temperature, pressure, &c., that Faraday refers the annual and diurnal variation of the needle, and other periodical changes to which it is subject. Thus the position of the sun at a given place affects the atmosphere, the atmosphere affects the direction of the lines of force, the lines of force there affect those at any distance, and those affect the needles which they respectively govern. The sole action of the atmosphere is to bend the lines of force, whilst the needle, being held by these lines, changes in position with the change of the lines. The needle is, in fact, a sort of balance, on which all the magnetic power around a given place hangs. Its mean position is the normal position. The fixation of the lines of force on the earth brings the needle back from its disturbed to this normal state; thus, as the earth rolls on in its annual course, that which at one time was the cooler becomes the warmer hemisphere, and in its turn sinks as far below the average magnetic intensity as it before stood above it. Now, since the sum of the forces passing out from the earth, wherever there is dip, must correspond on each side of the magnetic equator, it is impossible that they should become more intense in one hemisphere or more feeble in the other without corresponding effects upon the position of the magnetic equator itself, which may be thus expected to undulate, as it were, with the force, and move alternately north and south every year.

In the case of the diurnal variation, the whole portion of the atmosphere exposed to the sun receives power to refract the lines of force, and the whole of that which covers the darker hemisphere assumes an equally altered but contrary state. It is as if the earth were inclosed within two enormous magnetic lenses, competent to affect the direction of the lines of force passing through them.

This hypothesis does not assume that the heated or cooled air has become actually magnetic, but is changed only in its power of transmitting the lines of magnetic force. It does not at present profess to apply to the magnetic or great secular changes of terrestrial magnetism, or to the cause of the magnetic state of the earth itself. With respect to variations of magnetic force not periodic but irregular, Faraday re-

*The author of this work first pointed out the necessity of placing the oscillating magnet in a space as nearly approaching a vacuum as possible.

fers them to varying pressure, winds, currents, precipitations of rain or snow, &c., all of which may change the magnetic conduction of the air; and in this way the presence of a mere cloud near a station may do more than the rising sun. Where the air is changed in temperature or volume, there it acts and there it alters the directions of the lines of force, and these by their tension carry on the effect to more distant lines, whose needles thus become affected also.

247. Theoretical review of ordinary magnetic action.—The first idea of ordinary magnetic phenomena was, as we have seen, the doctrine of Thales, who conceived the magnet to possess a species of animation; this doctrine, however, was superseded by the doctrine of magnetic effluvia, a principle which engaged the attention of philosophers down to the time of the celebrated Boyle. Lucretius, in his fine poem "*De Rerum Naturâ*," supposes that in the attraction of iron the effluvium of the lodestone displaced the surrounding air, in consequence of which atoms of iron flew toward the void, and in doing so dragged the iron toward the lodestone. Following this hypothesis arose the notion of an expansion and contraction of the effluvia, which, being thrown outward from the magnet, seized upon ferruginous matter, and drew it by a collapse to the magnetic pole. Boyle resolves magnetic effluvia into indefinitely small atoms of magnetic iron, so indefinitely small as to permeate solid substances, and thus the lodestone is enabled to seize upon iron so forcibly as to raise it against its own gravity. Gilbert imagines magnetic force to depend on what he calls "a formal efficiency," a "form of primary globes," of which forms there is one in the sun, one in the earth, another in the moon. Magnetism is the "formal efficiency" peculiar to the earth. The views of this truly great philosopher are, it must be allowed, very obscurely expressed, and, in common with all the preceding, were never practically applied in physico-mathematical science.

248. Descartes, casting aside all preceding doctrines, applied his famous system of vortices of ethereal fluid in explanation of magnetic action. The Cartesian hypothesis supposes matter to be indefinitely extensible without any other property, and to consist of atoms of different forms—every other quality being derived from ethereal elastic fluid continually revolving in vortices or eddies of various orders. The magnetic curves he thinks an evidence of this. In no instance has the reasoning of this distinguished man been so persuasive as in the application of his theory to the phenomena of magnetism.

249. Dr. Gowen Knight supposes magnetic action to depend on the circulation of a repellent fluid existing in space and in the pores of steel, and capable of passing in and out of the magnet, or between magnetic poles, in one direction only. This hypothesis he thinks consistent with the observed phenomena. If, he says, a reason can be assigned for this circulation, then the "whole mystery of magnetism is solved." Attraction, upon this hypothesis, is the result of the fluid circulating from the pole of one magnet to the pole of another, Fig. 16. Repulsion, on the contrary, is the result of opposed streams, Fig. 17. Dr. Knight's work is

by no means undeserving of notice, as being one of the first attempts to account for magnetic phenomena through the mechanics of matter and motion; and although strong exceptions have been taken to his postulates, the question how far they lead us to conclusions in accordance with observation still remains to be considered; of the agents employed by nature we really know nothing, except by the assimilation of effects with other agencies familiar to us. One of the great objections taken to this hypothesis is, that it is irreconcilable with the particular law of force deduced by Lambert and Coulomb, and should therefore be discarded. This is, however, a somewhat hasty conclusion, since we have already seen, both experimentally and by the researches of Faraday, that magnetism is not necessarily a central force, and that the law deduced by Coulomb and other philosophers is only a particular case of a more general form of magnetic action.

250. It is not unworthy of remark, that soon after the discovery of electro-magnetism in 1819, Ampère developed his beautiful electro-dynamic theory, and showed the mutual attractions and repulsions of electrical currents according to a certain fundamental law; by assuming for a magnet a peculiar structure, he brings it under the dominion of this law, and by a most beautiful experiment shows that the circulation of electrical currents in a spiral wire, Fig. 41, imparts to that wire all the properties of polarity in the direction of its length; and is finally led to conclude that a magnet has a current of electric fluid circulating about it in planes nearly perpendicular to its axis.

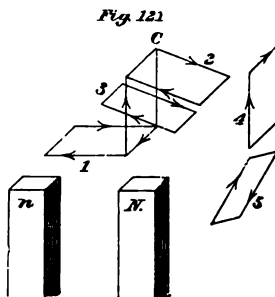
251. Following Dr. Knight's work, we have the fine work of Æpinus, in which the author supposes the existence of an ethereal fluid, termed the magnetic fluid, the particles of which repulse each other, but attract, and are attracted by, the particles of ferruginous matter. He further supposes that, in the absence of this magnetic fluid, the particles of ferruginous bodies also repulse each other, but attract the magnetic fluid; all these attractions and repulsions conform to the general law of central forces, being as the squares of the distances inversely. Æpinus had the great merit of reducing the laws of equilibrium of such a fluid and common matter to strict mathematical investigation, and of affording, in a great majority of cases, a satisfactory explanation of the phenomena. According to the hypothesis of Æpinus, the condition of a magnet is an induced disturbance of the magnetic fluid it contains, from which results a redundancy or accumulation of fluid in one pole, and a deficiency, or what may be termed a redundant matter, in the other. This positive and this negative pole attract each other because of the mutual attraction between the redundant fluid of the positive pole and the redundant matter of the negative pole. Two positive poles repulse each other from the mutual repulsion of the particles of the magnetic fluid; two negative poles also repulse each other in consequence of the repulsion of the particles of redundant matter. Induction is the result of similar attractions and repulsions upon the magnetic fluid and ferruginous matter or distant iron by an overcharged or undercharged pole.

252. The French philosophers, startled at the assumption of a repulsive force in the particles of common matter, as being contrary to a fundamental law of gravity, changed the terms of the hypothesis of *Æpinus*, without altering virtually its application. Having assumed the existence of a primary magnetic fluid, they supposed it to be a compound of two elementary principles, an austral and a boreal fluid, each repulsive of their own particles, but attractive of each other. Magnetic action is the result of a separation of these elementary fluids in each particle of the mass, and to which they are confined. This hypothesis originated with Coulomb about the year 1780, after the discovery of the opposite electricities, and the electrical theories of Du Fay and Symmer. It has since been more especially carried out in all its generality by M. Poisson, in his elaborate and mathematical analysis of the phenomena of magnetism. M. Poisson proves that the sum of the actions of the magnetic elements in a given magnet are the same as if they proceeded from a thin stratum of each fluid occupying the surface only, and so distributed that their total action upon the interior of the body is equal to zero. We have only to substitute the term austral fluid for redundant matter or deficient fluid, and we have nearly the same result. Bonnycastle, in his application of this hypothesis, conceives the two fluids to have accumulated in opposite parts of a magnet, which would make it identical with the hypothesis of *Æpinus*, by only changing the terms; whilst Barlow confines the action to the surface of the magnet altogether, and refers the respective centers of force to two centers indefinitely near each other in the center of attraction of the surface.

We have rather dwelt on these views of *Æpinus* and the French philosophers because of their admitting of the application of strict mathematical reasoning, and because of their being generally received as adequate to the explanation of magnetic action, no other equally substantive theories having been hitherto proposed; we must not, however, imagine that either of these hypotheses furnishes a real explanation of magnetic force, or that the existence of a magnetic fluid or fluids is, after all, anything more than a fiction of the mind, employed as a temporary substitute for truth. Still they greatly assist us in arriving at what we may consider as a true theory, viz, a resolving of classified facts into other facts still more general, and the final development of one great ultimate fact common to them all. Few who have considered the more recent progress of electricity and magnetism, more especially the brilliant researches of Faraday, will be disposed to place much confidence in the notion of electrical and magnetic fluids, and who will not perceive that the phenomena depend in all probability upon a principle of causation of a very different character. Grove, reasoning on the correlation of physical forces, considers magnetism as a mode of motion caused by certain undulations or vibrations in the particles of common matter. Faraday, as we have seen, disencumbers himself of the common theory of material atoms, and refers the phenomena to certain lines of force traversing space and the relations which various sub-

stances have to these lines. In all these speculations the student will do well to remember that it is quite in vain to seek for an adequate explanation of causation in the abstract; all we can hope to arrive at is, as just observed, the resolving of phenomena into an intelligible sequence, and showing their dependence on some great ultimate principle reducible to a fact. This it is which constitutes a perfect theory.

253. Employment of induced magneto-electric currents as a test and measure of magnetic force—Faraday's researches.—A piece of metal or conducting matter which moves across lines of magnetic force, has, or tends to have, a current of electricity produced in it, and the direction of the polarity of a magnet is determined by the *direction* of the electric current produced in it during the motion. Thus, if N represents a magnetic pole, and over it a circuit be formed of metal of any shape, and which at first is in a position C; then, if that circuit be moved in one direction into position 1, or in the contrary direction into positions 2, 3, 4, and 5; or if, the first position C being retained, the pole move to or towards the position n, then an electric current will be produced in the circuit, having in every case the same direction, being that marked by the arrows. Reverse motions give currents in the reverse direction.

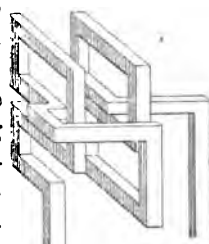


No inductive effect is produced by the mere *rotation* of a bar magnet, and no currents are produced in a wire revolving with the magnet; but if the wire rotates whilst the bar is stationary, or if the bar rotates while the wire is stationary, currents are produced.

The magnetic forces are distributed in and round a bar magnet in the simplest and most regular manner, so that any wire or line proceeding from a point in the magnetic equator of the bar, so as to pass through the magnetic axis to a point on the opposite side of the magnetic equator, must intersect *all* the lines in the plane through which it passes, and a wire ring, somewhat larger than the magnet, held edgewise at one of the poles, and then turned 90° and carried over the pole to the equator, intersects *once*, all, or nearly all, the lines of the magnet.

In experimenting on the currents produced in wires when they cross the lines of magnetic force, Faraday employed a galvanometer (Fig. 122) in which the conducting coil was cut out of plates of copper, so as to form a square band 0.2 of an inch in thickness, which passed twice round the vibration plane of each needle, the length of the metal round the needles being 24 inches, the fine long wire of the coil galvanometer offering too great an obstruction to the passage of currents of such feeble intensity. These galvanometers proved far more sensible than the fine wire instruments; the mere passage

Fig. 122.



of a wire loop *once* between the poles of a horseshoe magnet (Fig. 123) capable of supporting 40 lbs. being sufficient to cause a swing of the needle through 90° .

It was found necessary, in order to obtain uniform results, that the wire should be moved with the *same* velocity, and should be of the *same* thickness and of the *same* metal.

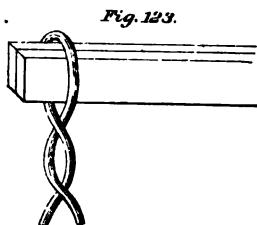
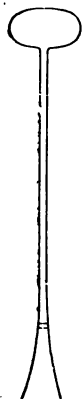


Fig. 123.

By the term *magnetic polarity*, Faraday understands the opposite and antithetical actions which are manifested at the opposite ends of a portion of a *line of force*, and he regards the indications of the moving wire as most valuable,* because it

shows the full amount of magnetic power without in the least disturbing the disposition of that power. The *amount* of current induced is precisely proportionate to the amount of lines of magnetic force intersected by the moving wire in which the electric current is generated and appears. Thus, on introducing a bar magnet into the loop (Fig. 124), and leaving it there, a deflection of 8° was constantly produced at the galvanometer; *two* introductions (the electric current being broken by removing one or other of the terminals of the loop from the mercury cup of the galvanometer, previous to removing the magnet) produced a deflection of 15.75° ; *three* introductions produced a deflection of 28.87° ; and *four*, a deflection of 31.66° .

Fig. 124.



For experimenting with the magnetic force of the *earth*, the form of moving wire employed was in the form of a rectangle or ring, which was caused to rotate, and the currents produced gathered up by a commutator and sent on to the galvanometer to be measured. There is this difference between the magnet and the earth in their action on the moving wire. If a loop be placed over a magnet, it incloses *all the lines of force* belonging to it; therefore the greater the number of convolutions of that loop, the greater the amount of electricity induced. The contrary is the case with regard to the earth's magnetic force; here the lines of force intersected are as the *areas* of the moving rectangles.

Faraday thinks that, by improved arrangements, the moving wire may hereafter be applied with advantage to the investigation of the earth's magnetic force in different latitudes and places. The axis of rotation must be perpendicular to the lines of force, *i. e.*, to the *dip*.

254. Analogy of a magnet with a voltaic battery and an electric conductor polarized by induction.—As far as regards the disposition of the *external*

* The pointing of a substance is an effect dependent on media and circumstances; *e. g.* a weak solution of *protosulphate of iron*, if surrounded by water, will, in the magnetic field, point *axially*, but if in a solution stronger than itself, it will point *equatorially*.

In a field of *equal force*, a magnetic needle cannot show polarity, as the very fact of pointing implies a disturbance of the equality of arrangement of force.

lines of force, the analogy is perfect. Faraday magnetized to saturation a very hard steel bar 12 inches long, 1 inch broad, and 0.05 inch thick; its power, as measured by the moving wire, was 6.9° . It was now broken into two pieces nearly in the middle; one half had a power of 5.94° , the other of 5.89° . The two pieces, placed side by side with similar poles, together as a compound magnet, had a power of 11.06° , not much below the sum of the powers of each half ascertained separately, and the loss on each half, as compared with the original bar, was not greater than was to be expected, considering the saturated state of the original magnet.

This is quite in harmony with the voltaic battery, for it is well known that if a battery of twenty plates be separated into two of ten or four of five pairs, each of the smaller batteries can supply as much dynamic electricity as the original battery, provided there be no obstruction to the passage of the current.

But in neither the battery nor the conductor are the lines of force continued *internally*, as is the case with the magnet. Consequently, on separating the conductor or insulated battery in the middle, no change appears there, nor any origin of new lines of inductive force, but the two divided portions remain in *opposite states*, or absolutely changed. In the magnet, on the other hand, there is on division a development of new external lines of force, and no absolute change of northness or southness, because the lines of force are continuous through the body of the magnet.

It has been shown by Ampère and Davy that an electric current has a tendency to *elongate* itself, and that like electric currents *attract* each other; but a magnetic "axis of power" has a tendency to *shorten* itself, and like magnetic lines of force exert mutual *repulsion*. Here a contrast between the electric and magnetic forces seems to be demonstrated, but in reality there is again a coincidence, because the two axes of power are at right angles to each other. Again, *unlike* magnetic lines, when *end on*, as when similar magnetic poles are face to face, *repel*; so, also, unlike electric currents, when in the same relation, *repel* also. Like electric forces, when end on, *coalesce*; like magnetic forces do the same. Like electric currents end to end do not add to their sums; the quantity of electricity circulating in a battery is not increased by adding to the number of the plates; and like magnetic "lines of force" do not increase each other. Lastly, *like* electric currents side by side (a voltaic battery with large plates compared with one with small plates) add their quantities together, and *like* magnetic forces do the same.

255. Condition of a magnet.—Faraday considers the condition of a magnet to be similar to that of a voltaic battery immersed in water, or to a *gymnotus* or *torpedo*, when these fish, at their will, fill the surrounding fluid with lines of electric force. The direction of these lines may be traced in the water round the battery by a magnetic needle or by

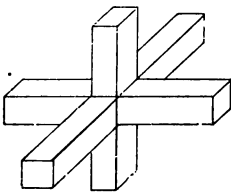
the galvanometer; there is probably just such a medium (magnetically speaking) round a magnet in free space.

In a horseshoe magnet the lines of force are greatly distorted. The line of maximum forces from pole to pole grows up as the horseshoe form is more completely given, the power gathering in and accumulating about this line, because the bad conducting space between the poles is shortened. A bent voltaic battery or a gymnotus, curved at the moment of its action, presents like results.

The action of the keeper in reducing the power of the magnet in the space around is evident: a good conductor is substituted for a bad, and hence more power is transmitted through it, and less through space. Again, when a magnet is charged to saturation with the keeper on, it falls in power when the keeper is removed, because the keeper, while on, in consequence of its excellent conducting power, enables the magnet to take up and sustain a higher condition of charge, which faculty it loses when the keeper is removed. The same explanation applies to the well known fact, that a magnet will receive a much higher charge when a piece of iron is in contact with its poles than when it is surrounded with the lower paramagnetic air. It also shows why the armature of the lodestone is useful. A magnet when charged to supersaturation loses its power when left alone; but if the feeble magnet-conducting air be replaced by a body of good conducting power, as when a magnet is surrounded by iron, it retains its power.

256. Places of no magnetic action.—Faraday arranged six electro-magnets in the position shown in Fig. 125, so that, when excited, their

Fig. 125.

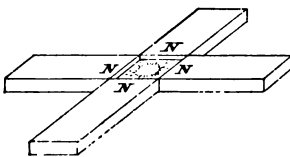


poles were together in such a manner as to include a cubical space or chamber, to which access could be obtained either by removing a portion of the solid angles of the ends, or by drawing one of the electro-magnets a little way from the others. A small magnetic needle, hung in the middle of this space, gave no indication of any magnetic power; iron filings sprinkled on a card were not af-

fectured in the middle part, nor could any inductive effects be obtained by the rotation of a ring helix. The chamber was in fact the analogue of the space presented within a deep metallic vessel when charged with electricity.

Similar phenomena may be obtained with ordinary magnets placed

Fig. 126.

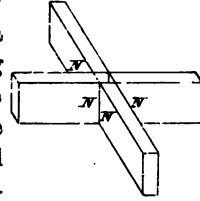


with their similar poles together, as in Fig. 126. Iron filings sprinkled on a pasteboard tray may be examined in the chamber of Fig. 126, and a small magnetic needle may be introduced into the vertical chamber of Fig. 127.

"Contemplating," says Faraday, "a bar magnet by itself, I see in it a source of dual

power. I believe its dualities are especially related to each other, and cannot exist but by that relation. I think that though related through the magnet by sustaining power, they are not so related by discharging or inducing power, a power equal in amount to the coercitive or sustaining power. The relation externally appears to me to be through the space around the magnet; in which space a sphondyloid of power is present, consisting of closed curves of magnetic force. That the space is not mag-

Fig. 127



netically dark appears to me by this, that when bodies occupy that space having like relation by known phenomena to the power as the space has—as copper, mercury, &c.—they produce magneto-electric currents, when moved. When bodies (media) occupy the space around the magnet, they modify its capability of transmitting and relaxing the dual force of the magnet, and, as they increase or diminish that capability are paramagnetic or diamagnetic in their nature, giving rise to the phenomena which comes under the term of magnetic conduction. The same magnet can hold different charges as the medium connecting its poles varies, and so one fully charged with a good medium (such as iron) between its poles falls in power where the iron is replaced by air, or by space, or by bismuth. The medium about a magnet may be mixed in its nature, and then more dual power is disposed of through the better conductor than the worse, but the whole *amount* of power remains unchanged. The powers, and utility of the media and of space itself fail, if the dual force or polar action be interrupted. The magnet could not exist without a surrounding medium or space, and would be extinguished if deprived of it, and *is* extinguished if the space be occupied adversely by the dual power of a dominant magnet of sufficient force.

The polarity of each line of force is in the same direction throughout the whole of its closed course. Pointing in one direction or another is a differential action, due to the convergence or divergence of the lines of force upon the substance acted on, according as it is a better or worse conductor of the magnetic force."

MAGNETISM.

PART II.

CHAPTER I.

GENERAL MAGNETICAL PRINCIPLES AND PHENOMENA.

1. *Magnetism*, from the mysterious character of its phenomena, has always been a subject of popular interest and experiment. As an *actuating* power, its relation to the wonderful performances of the electric-telegraph, in these modern times, has given to it an immense advance in the scale of practical sciences. As a *directing* agency, it has long been known and valued in navigation, mining, surveying, &c., as affording to the sailor, especially, under circumstances favorable to correct compass action, safe and beneficial guidance in trackless seas, and under dark or obscure skies. It has also, on the other hand, assumed, especially in late years, a grave position of importance, as a *misguiding influence*, tending, by its disturbance of the compass and fitful changes of disturbing force, to the serious endangering, under circumstances not contemplated or understood, of life and property by a fallacious confidence.

2. *Universal prevalence of magnetism in physical substances*.—Magnetism is an essential force or property in the constitution of all material substances, and is one of the mighty agencies by which nature is subordinated to the will, and performs the destiny and uses appointed of the Great Creator. It is inseparably associated with electricity (but is not, as has been popularly assumed, identical with it), as also with caloric or the matter of heat, and with other subtle influences productive of chemical affinities, solidity, &c. But, whilst thus existing, in common, in material substances, they are usually in a latent or neutral condition, so as, in the natural and quiescent state of things, not to be ordinarily perceptible.

3. *Apparent relation of magnetism, electricity, chemical action, light, heat*.—None of these different principles—magnetism, electricity, chemical affinity, light, heat—appear to be of primary or independent nature, but rather attributes or qualities of some unseen and unknown *master agency*, the common parent of all. For that none is essentially *master*, we infer from the experimental fact, that each one, in turn, may be made to elicit or produce the others. Thus, by the agency of *magnetism* we can develop electricity, heat, chemical action, as well as light. So, by means of *electricity*, we can produce all the others. By *chemical action*, too, we obtain the like results. By heat, again, we produce chemical changes, magnetism, electricity, and light. And, by means of light, chemical action, heat, electricity, are producible, and magnetism also.

4. *Iron, as a material, the most highly susceptible of magnetism*.—Magnet-

ism has its most striking and powerful developments in iron, or other descriptions of ferruginous material. But certain other metals, such as nickel, cobalt, magnesia, and chromium, are, in inferior degree, susceptible of the magnetic condition.

5. *Two qualities or polarities always coexisting.*—Like electricity, magnetism has two qualities always coexisting in the same mass of material, and, in the case of magnetism, residing, apparently, in every molecule or particle of matter. The diverse qualities, which in electricity are named *positive* and *negative*, are, in magnetism, popularly distinguished as *northern* and *southern* polarities; more technically they are designated *plus* and *minus*; otherwise, again, as *boreal* and *austral*. Another form of denomination of the two polarities, for reasons hereafter noticed, as occasion for deviation from the more popular names seems to require, is employed in the following pages.

6. *Poles of magnets.*—In magnetic bars, or other forms of magnets in which the length of the integral plates or bars greatly exceeds the other dimensions, the polarities are the strongest at or near the extremities, and weakest, indeed quite insensible, about the middle. Hence, because of the tendency to concentrated action there, the extremities are denominated the *poles*; whilst the neutral line or place in the middle, separating the two polarities, is considered as the *equator* of the magnetic body.

7. *Dissimilar poles attract each other, and similar repel.*—The two polarities, it should be always borne in mind, are reciprocally *attractive* of one another, while each of them is essentially *repellant* of its own kind. Thus the northern attracts the southern, and the converse; whilst the northern repels the northern and the southern repels the southern. Any exception to this law can only be *apparent*. In the case of a small or weak magnet being placed with one of its poles in contact with the similar pole of a powerful magnet, or very close to such pole, attraction may take place instead of repulsion; but this will be found to be due to the overwhelming energy of the master-magnet in inverting the polarity of the other, and so attracting it.

8. *Tests of magnetism.*—The existence of the magnetic condition, in its *sensible* form, is usually shown by the tests of attracting pieces of iron, or iron filings, and, more delicately, of causing deflection or movement in the needle of a compass. A sewing needle, when duly magnetized and suspended by some fibers of floss silk, or a fine hair, becomes a very delicate test of the existence of the magnetic condition. The *denomination* of the polarity in any portion or place in a magnetic body thus determined, is shown by the *nature* of the influence exerted on the known poles of the needle. Thus, in the use of the poised magnetic needle, as a test, we may learn with certainty these two things: (1) that the bar or substance which influences the needle of the compass is actually magnetic; and (2) that the part attracting the north of the needle must have southerly polarity, or, attracting the south, northern.

9. *Magnetic repulsion.*—Whilst the property of magnetic attraction is so simply shown by the familiar process of the sustaining of magnetizable substances, *repulsion* is not indicated without the aid of a substance rigidly and positively of contrary polarity. Thus any magnet will attract a piece of soft iron with either pole alike; but when either pole is placed in contact with the *same pole* of another equally hard and powerful magnet, there will not only be no adhesion, but a repellant action, sometimes of sensible force, and, in any case, sufficient, if one of the magnets be so placed as to be freely movable, to turn it aside, or quite round. Where one of the magnets is suspended by a thread, or on a pivot, as in the compass-needle, then the repulsion of similar poles will generally be shown, however small or weak the movable needle may be in comparison with the actuating magnet.

10. *The two polarities not separable.*—The two polarities, though they may be molecularly decomposed, are not only naturally and essentially coexistent, and cannot be produced the one without the other; but they cannot be separated, or comprised separately, in any single detached magnetic mass; and wherever they *appear* to be separated, as in the two ends of the same magnetic bar, the separation is but conditional and relative—being dependent on the preservation of the bar in its original unbroken continuity.

11. *Experimental verification.*—This proposition may, conclusively, be verified by a very easy experiment. Take a plate of steel, a compass-needle for instance, or a steel wire, or a narrow busk-steel plate, and when in a proper magnetic state it will be found, by the effect on a small compass, or on a common sewing-needle (if magnetized and suspended by a hair or fine thread), that the whole of each half is of distinctive polarity—that is, one half wholly of northern and the other wholly of southern. Now here, *if it were possible*, we could easily obtain and secure each polarity separately by breaking the plate or needle in the middle. On trying the experiment, however, we shall find that each half, instead of exhibiting an uniform polarity, has suddenly changed to a distinct magnet with its separate and proportional force of polarity at the ends—the end of the southern portion, which was originally neutral, being now a strong north pole, and the original neutral place of the other section being a south pole. A similar result will be obtained if the plate be divided into several pieces, each piece, as soon as separated from the parent mass, becoming a true and independent magnet, but necessarily, because of the loss of material, of diminished power.

12. *The quantity of each polarity always equal.*—As the two polarities cannot be separated, nor either of them produced or elicited separately, neither can they be produced in unequal measure or quantity. Hence, if by any magnetizing process we should produce a *northern* polarity in any piece or body of magnetizable substance, that development will produce spontaneously, and in precisely corresponding quantity, the *southern* polarity in another part of the same substance. In one part,

indeed, especially where polarity is given only to the extremity of a bar or plate of hard iron or of steel, the primary polarity may be strong and energetic, and in the opposite end or side weak, or scarcely apparent; but, however more extensively diffused, the relative quantities of the northern and southern polarities must be equal.

13. Consequential pole and its power of propagation.—In soft malleable iron, as in a key for instance, when put in contact with, or suspended from, the pole of a magnet, the second or *consequential* pole will be always found at the lower extremity, or the end most distant from the magnet, and of the same denomination as that of the magnet's attracting pole. Thus the north pole of the magnet will produce southern polarity in the nearest end of the key, and that polarity the northern, consequentially, in the other end. And as this lower polarity, in the case of soft iron, will have a degree of energy in some measure correspondent with the attracting force above, it will be endued with a propagating power of the nature of that of the original magnet, so as, in its turn, to elicit polarity, and then to attract it, in a second key; and that, if the primary power be sufficiently great, to do the same with a third key, and so on. The pole of a very powerful straight-bar magnet may, in this way, be made to sustain a chain of keys, three or four in continuity, each key being in itself a separate magnet, whilst so situated, with its southern pole above (the north end of the magnet being employed) and its northern pole below; whilst in the employment of smaller substances, such as small polished bits of iron wire, sprig nails, or small balls of soft iron, the series may sometimes be run to an extent of ten or fifteen or even more in one chain.

CHAPTER II.

On the inductive or magnetic developing power of the magnet.—Magnetization, with new and powerful processes.

I.—THE INDUCTIVE POWER OF THE MAGNET.

14. General character or definition of induction.—The well-known property of the magnet of producing or eliciting the magnetic condition in other pieces of steel or iron, is the property popularly distinguished by the term *induction*—a property on which the attraction of iron, and the magnetizing processes effected by the aid of magnetical instruments, or other apparatus having magnetic polarity, are dependent.

15. Each pole of the magnet induces converse polarity.—As the two opposite polarities attract each other, and the same kinds repel, so each polarity always tends to develop or elicit the opposite kind of magnetism in any piece of iron or steel to which the magnetic pole may be applied or brought near.

16. Principle of attraction by the magnet of previously unmagnetic substances.—In this case of *attraction*, the inductive power of either pole of

the magnet, it is plain, first elicits a polarity opposite in kind to its own and then attracts it. Hence it follows, that attraction betwixt a magnet and an *unmagnetic* substance, or a substance devoid, at the time, of any sensible magnetism, can only take place when the magnet, by its own peculiar virtue, is able to elicit the magnetic condition in such substance, and that with a polarity contrary to its own.

17. *Two effects of simple induction.*—The induction of simple contact, or of close proximity, *without motion*, or manipulation, is of two kinds, as to the ultimate effect of the influence exerted—the one transient, disappearing as in the case of pure soft iron with the removal of the inducing magnet; the other remaining, with more or less permanency (as to a portion of the induced development), being sustained by the coercive force of the material acted on.

All kinds of iron and steel, in the metallic state, are susceptible of simple induction of the first or *transient quality*, from the softest and purest iron, where it is greatest, to the hardest steel and cast iron, where it is comparatively small; and all the harder kinds of the metal derive, from contact with a powerful magnet, some *residual influence*, in the proportion, inversely, of the respective rigidity or coercive force of each particular specimen.

18. *Experiments on the two effects of induction.*—These effects may be thus characteristically exemplified:

(1) *The transient induction.*—Attach a short bar of iron, a key, or other piece of soft malleable iron, to the pole of a magnet, or place it with one of its extremities near to such pole, and the iron, as we have seen, will become a true magnet, and it will remain such as long as its proximity with the permanent magnet is maintained. But, instantly, on removing it away from the magnet, the polarity of the iron, to any obvious extent, will disappear.

(2) *Residual polarity.*—If now, instead of a piece of *soft iron*, we apply a small bar or needle of steel, of cast iron, or of hard hammered malleable iron, to the pole of a powerful magnet, this will also become inductively magnetic, though not so strongly as the soft iron; and, when removed from the magnet, a portion, probably of but feeble force, of the polarity will be retained. In this case, the inherent coercive quality of the material resists the return, in the magnetical elements, to a state of neutrality, on the same principle as the polarity of regularly constructed magnets is sustained and, in degree, made permanent.

19. *Magnetic coercive force.*—The coercive force in the constitution of metallic iron and its several kindred qualities is the property by which facility of magnetization is opposed and permanency of the magnetic condition secured. It differs, in degree, in every variety of the metal and its ores. It is the least (ordinarily not observable) in soft pure iron, becomes very sensible in hard, or crystalline, or hammered malleable iron, and increases in the several qualities of *cast iron* up to a degree which renders, as I found, this comparatively inexpensive material

adequate for the construction of powerful permanent magnets. In steel, the coercive force has the greatest range, being very feeble in soft and bad qualities, and extremely strong and enduring in steel of the best qualities (that is, in steel converted out of the highest qualities of iron), and the most so in thin plates of the greatest degree of hardness. And, finally, in certain magnetic iron ores, such as the *loadstone*, the rigidity or power of retention of the magnetic condition is, in the best qualities of the mineral, greatest of all.

20. Relation of facility of induction and permanency.—These follow a converse rule. Hence in the magnetizing effects of simple induction, the kinds of iron or steel which realize the attractive force most easily and fully, or have the smallest coercive force, generally lose the magnetic condition with proportional facility—pure soft iron, as we have shown, instantly and entirely as the actuating magnet is withdrawn, whilst hard iron and steel in any of their kinds or qualities usually retain a portion of the magnetic development.

21. Contact, or very close proximity, not essential for inductive action.—A remarkable law of induction is the power of acting magnetically at considerable distances, and with a degree of energy entirely unaffected by the interposition of the most solid non-magnetic substances. Nor is the power of magnetic induction prevented, though it is necessarily modified in its action, even by the interposition of iron, steel, or actual magnets. By contact, the most powerful inductive effects are of course produced; but at small or moderate distances from the extremity, or pole, for instance, of a powerful straight-bar magnet, all the phenomena elicited by contact (though in a rapidly diminishing ratio) may be produced.

22. Illustrative examples of powerful induction without contact.—If we place a strong bar magnet on a pedestal or support, we may attach to each of its poles, as we have seen, keys, or other pieces of polished iron, and under the power of propagating the magnetic condition from piece to piece, we may attach a second, third, &c., in considerable series, according to the power of the magnet. But the same thing, though to an inferior extent, may be effected *without contact*, so that, placing the flat of the hand, or a piece of brass, wood, or glass, betwixt the pole of the magnet and the primary key, it may be made to suspend (in the employment of a very powerful magnet) a second, or even a third, notwithstanding the separation, and entirely uninfluenced by the quality of the substances interposed.

23. Ratio of diminution of the power of induction in respect of distance.—The ratio in which the inductive force of either pole of a magnet acts on a piece of iron when separated from contact and tried at different distances, follows the law, as to diminution of the power, of the square of the distance, *inversely*—a law and progress of diminution which, in simplest form of expression, amounts to this, that, if at the distance of a given space, say an inch, from the extremity or pole of a long straight

magnet, the magnetic or inductive force be called 1, then, at the distance of 2 inches the force will be reduced in the inverse proportion of the squares of the two distances, or as the square of $2=4$ to the square of $1=1$, or as 4 to 1. In other words, if the magnetic force at 1 inch distance be called 1, that at 2 inches would be as the square, inversely, of 2, equal to one-fourth, at 3 inches to one-ninth, at 4 inches to one-sixteenth, &c.

24. *Absolute reduction of influence by distance still more rapid.*—The proportions of magnetic influence with respect to distance, as just stated, if a magnet could be had with but *one pole*, would be found nearly correct at all distances; but, when the distances are increased to anything like the length of the inducing magnet, and much more beyond it, the progress of diminution in the power is found, by experiment, to be much more rapid. This arises from the converse action of the opposite pole of the magnet, in counteracting, in its due proportion with respect to distance, the primary inductive force. Thus, taking the distances of one and two lengths of the magnet, we find the proportions of influence to run thus: At one length distance, calling the force of the nearest pole of the bar 1, we should have this reduced, by the square of the distance of the counteracting pole, inversely, or $\frac{1}{4}$, giving $1-\frac{1}{4}=\frac{3}{4}$, for the correct expression of the power of the whole bar. In the case of two lengths distance, then, the power of the nearest end as represented by the square of 2, inversely, or expressed fractionally, equal to $\frac{1}{4}$, would be diminished by a force equal to the square of 3, inversely, or $\frac{1}{9}$, representing the whole power at this distance by the fraction $(\frac{1}{4}-\frac{1}{9})=\frac{5}{36}$ —thus giving the respective powers of the magnet, at 1 and 2 lengths, the proportion of $\frac{3}{4}$ to $\frac{5}{36}$, or 5.36 to 1, nearly. Thus, calculated in the same way, and tested by the deviations of a delicate compass-needle, the powers of a straight-bar magnet, acting at various distances and reckoned in measures (from 1 to 10) of the length of the bar, come out in this series—1, $\frac{5}{27}$, $\frac{7}{108}$, $\frac{3}{80}$, $\frac{17}{675}$, $\frac{13}{2232}$, $\frac{15}{2352}$, $\frac{17}{3888}$, $\frac{19}{8075}$, $\frac{21}{9075}$ —instead of 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{6}$, $\frac{1}{8}$, $\frac{1}{36}$, $\frac{1}{49}$, $\frac{1}{64}$, $\frac{1}{81}$, $\frac{1}{100}$, which would represent the ratio of diminution of the power of the bar magnet, with the increase of the distance, if the magnet had but one pole, or were of unlimited length.*

II.—MAGNETIZATION.

25. *Magnetization—Definition.*—Magnetization, in practical science, is the producing of permanent polarity in substances capable of receiving and retaining the magnetic condition. This operation consists in the due application of extraneous magnetic force, for the decomposition

* This series of proportions requires, for strict accuracy, some correction, on account of the real actuating force of either end of a magnet not residing precisely at the extremities, but a little within. The nature and quantity of the correction requisite have been shown in a paper of mine in the "New Edinburgh Philosophical Journal," for April, 1832, where the *deviating* action of a bar magnet, or set of magnets, on a compass at various and considerable distances, is adopted for the purpose of measuring distances through intervening masses of rock, and so applied to practical engineering for determining the thickness of rock or other material betwixt two opposite and approaching headways in tunneling and mining.

of mutually attracting and combined qualities, or the development of properties or powers previously latent or dormant, in the metal acted on. The two polarities appear to reside in, or in connection with, each particle or molecule of the iron (as before noted), in respect of which they are susceptible of movement and arrangement, but from which, as belonging to the very constitution of matter, they cannot be separated. Magnetization, therefore, may be considered as an arrangement, elementally, of the two polarities, giving the *effect* of a decomposition, in which an accumulation of energy is, in the most effective modes of the process, given to the two extremities of a steel bar in opposite denominations—the northern, at one end; the southern, at the other.

26. *Nothing added or infused by magnetization.*—That magnetizing *adds nothing* to the metal operated on, but only develops a previously dormant power, is demonstrably shown by the simple and well-known fact, that a strong and rigidly permanent magnet is able to produce the like magnetic state in thousands of steel bars without material loss to itself; and that, by certain processes of manipulation, such a magnet is capable of giving power to bars or plates adapted for large and powerful combinations, to an extent incomparably beyond its own, whilst its original energy may be but little, or possibly not sensibly, reduced.

27. *Theory of the magnetic development.*—Hence, if these views be correct, it may be inferred (in respect to the theory of the magnetic condition), that the power or polarity developed is derived from the favorable *arrangement* accomplished by the inductive magnet in the molecular magnetisms of the iron or steel acted upon. And this view of the phenomenon admits of some striking illustrations:

28. *Illustrations of theory.*—We may suppose, for instance, the particles or molecules of the ferruginous metal to be represented by a series of small short magnets, or of magnetized balls of hard steel, and the *mobility* of the molecules, or the magnetisms associated with them (as the theory implies), to be represented by suitable changes in the relative positions of the little magnets. Then we may illustrate what we suppose to be the two conditions of a steel bar—first, in its natural or neutral state; and secondly, in the magnetic state—in this manner:

(1) *The neutral state*—Fig. 1.

N.	$\overset{n}{\circ}$	$\overset{n}{\circ}$	$\overset{n}{\circ}$	$\overset{n}{\circ}$	$\overset{n}{\circ}$	$\overset{n}{\circ}$	S.	‡	C.
	$\underset{s}{\circ}$	$\underset{s}{\circ}$	$\underset{s}{\circ}$	$\underset{s}{\circ}$	$\underset{s}{\circ}$	$\underset{s}{\circ}$			

Let the annexed diagram represent a series of such magnetic particles, as if constituting a slight bar of iron or steel, N. S., with their respective polarities *n s*, cast transversely across the bar, either with similar poles, in parallelism, or alternate poles opposite to each other, or in any other way irregularly across. Such a series of magnets, if tested by a small compass placed near the end, as at C., would exhibit no polarity whatever, and might fairly represent the unmagnetic state of a steel bar. But, if we merely alter the arrangement, and place the polar axes of each ball (or little bar magnet) in the longitudinal direction so as to run in a continuous line, and with all their northern polar-

ities pointing one way and their southern the other, after the manner of this other series :

(2) *The magnetic arrangement*—Fig. 2.

N. nOs nOs nOs nOs nOs nOs S. ++ C.

Then we should have a representation, in the attraction of the north pole of the compass needle by the end S. of the series of balls, of the *magnetic* condition; and this attraction, on bringing the little magnets together with contrary poles in contact, would be found to be greatly increased, and the polarity at the extremities of considerable force.

29. *Magnetic arrangement illustrated by the voltaic combination.*—Another illustration of the effect of arrangement, and of the increase of intensity with relation to the number of the particles brought into the arrangement, is very well supplied by the voltaic pile or the ordinary galvanic battery. Here the several magnetic molecules of a bar of iron or steel may be represented by the separate cup, or cells, or pairs of plates in the galvanic combination. These molecular galvanisms, so to speak, however numerous they may be, can have no great external effects without particular and special arrangement. A thousand of them uncombined, or combined by wrong polarities, are all but powerless, and may thus serve to represent the *unmagnetic* condition. Arranged, however, with their respective metals, in proper alternate connection, we then obtain from the extremities of the series, energetic and powerful effects—effects generally proportionate in energy to the number or quantity of the series brought into connection. And here we have the representation of the *magnetic* condition, as well as of the varieties of intensity produced by difference of extent, or precision of adjustment, brought under the magnetic arrangement.

30. *Requirements for obtaining a permanent magnetic development.*—Our remarks here, as bearing on methods of magnetization of the most ready and convenient application, will have principal reference to the employment of permanent artificial magnets, as the master-power, in the operation. The requirement as to the *actuating force*, will hence be a good and powerful compound magnet of the U or horseshoe form, or a pair of strong (single or compound) straight-bar magnets. The requirement for the *recipient energy* will be a bar or bars of steel (hard cast-iron may do) of such rigidity, or coercive force, of molecular condition (19), as may enable the bar subjected to the magnetizing process to retain the polarity, at least in a large proportion, which may be developed.

III.—MAGNETIZING PROCESSES.

31. *General principle of the magnetizing processes.*—The object aimed at in these processes, is the application of the scientific principles of induction, connected with judicious forms of manipulation, &c., so as to elicit the highest intensity of the magnetic development of which the material acted upon is susceptible—a condition which has been denominated (though not very accordant with the strict meaning of the expression) *magnetic saturation*.

32. Simple and elementary processes of magnetization.—These familiar processes, having a certain measure of effectiveness adapted for the decomposition and arrangement of the magnetic elements in steel and other varieties of iron, are very various both in their modes of manipulation and their capabilities of development. Some of these it may be useful to notice.

(1) *The magnetic touch.*—If we merely cause one end of a steel bar or needle to touch the pole of a magnet, it will be found to have derived from the contact a slight magnetic development of the opposite denomination; and on touching the contrary pole of the magnet with the other end of the bar or needle, it will be found, however feeble in energy, to have become a true magnet. The magnetic development, indeed, will not, under this mode of operation, be either thorough and complete, or the arrangement of the molecular polarities regular and continuous; but the power developed in the ends will be sufficient, both for the attraction of iron filings or small bits of iron, and for enabling the bar or needle to take the direction of the compass-needle if suspended by a hair or thread. This, the simplest, perhaps, of magnetizing processes, originated, no doubt, the use of the expression of the *magnetic touch*.

(2) *Manipulation by one pole.*—If instead of mere contact of the end of a steel bar with the pole of a magnet we draw the bar across the pole from end to end, we obtain a much greater development of the magnetic condition. In this way, indeed, though only one pole is employed, we may elicit both polarities at the extremities of the steel, though not in equable degrees of concentration. For magnetizing small instruments, such as penknives, with a pretty strong magnet, all that is needful is thus effected, the point of the knife receiving the converse polarity from that of the magnet employed, and becoming strongly magnetic. Rubbing the blade backward and forward on the pole of the magnet, as the practice prevalently is, produces no benefit; it may be of much disadvantage. Two strokes on the pole of the magnet from heel to point, one on each side of the blade, drawing it quite off to a distance on both occasions, would generally be enough.

(3) *Apparent discrepancy.*—In this process, whilst the heel of the blade, commenced with, ultimately obtains the *same*, not the converse, polarity as that of the magnet made use of, there is no contravening of the law of development of converse polarities. At the instant of commencement, the north pole of the magnet develops southern polarity at the heel of the knife, but, as the stroke towards the point takes place, each part in succession obtains the southern quality, which, as the two polarities must be equally existing at the same time [5 and 10] spontaneously inverts the original kind behind it, so as to give to the terminal point the proper polarity due to the action of the north pole of the magnet.

(4) *Simple manipulation by both poles alternately.*—A magnetizing process, little less simple than those just described, which is of very convenient application, and will in many cases be found completely effective, is the following: Take a strong bar-magnet, and place square on

one of its poles, the plate or needle, by its middle, intended to be magnetized, as in the form of a T, the thick stem representing the bar-magnet, and the thin cross line the plate or needle. The arrangement, N S being the magnet, with its south pole, S, upward, and *s n* the steel plate or needle, will stand as in the diagram. Now, slide the plate off, either way (say from S to *n*), keeping it in close contact till it leaves the bar and passes clear off at its extremity; then, inverting the magnet, so as to place its north pole upward, replace the steel plate by its middle and with same side in contact as before, and slide it off by the contrary end, *s*. Repeating the process on the other side of the plate, taking care, by having the ends of the plate marked, so as to be easily distinguishable, to draw the plate from the middle to the end *n*, when the south pole of the magnet is upward, and the contrary way when the north is upward, and the operation, for small plates of steel, or needles, will generally be completely effective. A strong magnet of the horse shoe, or U, form may be used, with a like degree of efficacy under a similar method of manipulation.

IV.—ORIGINAL PROCESSES OR IMPROVEMENTS IN MAGNETISM.

33. For the practical objects herein contemplated, it will be sufficient to describe the process founded on that of Dr. Knight. For this operation, which is specially convenient for the magnetizing of bars or plates of the nature of compass needles, or for thin hard plates of steel of much larger dimensions, a pair of pretty large straight bar-magnets of considerable power, either single or compound, are requisite. Those usually employed are 15 inches to 24 inches in length, an inch and a half broad, and about half an inch in thickness. They are constructed of the best steel and made quite hard. The manipulation is thus conducted:

The two magnets being laid on a table in a straight line, with their opposite poles very near to each other, but not in contact, the plate or bar to be magnetized is laid flat upon the magnets, ranging in the same line, so as to extend equally over the surface of both. The bars are then drawn asunder, till the plate just rests with its extremities in contact with the extreme poles of the two magnets, and then it is slid off sideways, and removed to some distance, preserving the parallelism of its position with that of the magnets till these are restored to the proximity with which the operation commenced. The process is repeated with the other side of the plate in contact with the magnets, and in the case of thin small plates the condition of saturation is usually found to be obtained. Generally, however, to secure the maximum more satisfactorily, the plates are subjected to four strokes of the magnets, two on each side, and, in hard short bars, six or eight strokes are usually given, partly on the edges, as well as on the flat sides.

34. *General principle of Scoresby's method of magnetization.*—This original discovery in magnetizing processes may not be undeserving of particular description here, because of its superiority in effectiveness of magnetic development and rapidity of manipulation, over any

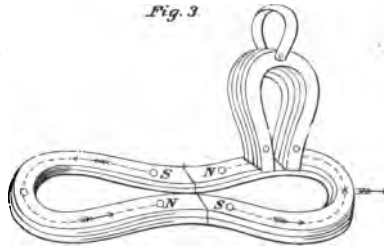
of the methods of magnetization by permanent magnets heretofore referred to, or publicly known, and the more so on account of its convenient applicability to compass-needles, and the large bar-magnets employed for the adjustment of compasses in iron ships. The novelty of the process consists in the interposing of a thin bar or plate of steel or iron betwixt the actuating magnet and the bars or plates to be magnetized. Its most characteristic advantages are realized where the species of magnet employed in the manipulation is of the *horseshoe* form. In the use of this instrument (the most convenient of all for the compass-maker, and, probably, too, for the manufacturer of "adjusting magnets") the ordinary methods of magnetization, by direct contact of the poles of the magnet with the surface of the bars acted on, all fail in producing a regular and continuous distribution of the magnetic elements throughout the extent of the bars, and especially in thin bars or plates of very hard steel. The general cause of failure here of the ordinary processes seems to arise from the production of consecutive poles. The action of a powerful horseshoe magnet applied directly to a hard thin plate or bar is *too local*, so that in the passage of its too closely contiguous poles a kind of magnetic wave is raised, highest under the magnet, which leaves behind it, probably, like the passage of a ship through the water, a series of other waves of diminishing altitude. By the interposition, however, of a thin bar of steel or plate of iron, the influence of the actuating magnetic polarity becomes diffused, whilst the more extended developing action serves, as it would seem, to yield an improved arrangement in the molecular magnetisms, and, hence, a higher and better result may be the general result.

35. Requirements.—The apparatus requisite for effective magnetization by Scoresby's method are a good compound magnet, or pair of magnets, and a plate or thin bar of iron or steel, as the medium of the magnetic development. Here the magnet may consist of two similar series or fasciculæ of straight bars fastened together in parallelism, with the opposite poles contiguous; or of a pair of such bundles of bars separate; or, what is most convenient and useful of all, of a strong compound magnet of the horseshoe form. The plates for being interposed may consist of thin slips of polished soft iron of the width and general form of the bars or plates to be operated on. For magnetizing compass-needles the length of these plates may be 8 to 12 inches, and the thickness about that of a shilling. For large bars, thicker and longer slips of iron (such as iron hooping) ground smooth on the flat sides will be needful. In the magnetizing of rather thin and hard plates or bars of the horseshoe form, a pair of bars of similar kind, of steel or iron, or a pair of the bars taken out of the general series designed for a compound magnet, may be employed.

36. Process for the magnetizing of bars of the horseshoe form.—The application, here, is to sets of bars of tolerably similar width and thickness. A pair of these, arranged in the form, nearly, of the figure , with converse poles in contact, are first placed on a table. Upon

these are then laid a pair of interposing bars or plates of similar size—a pair, for instance, of the series belonging to the instrument under magnetization. The process of manipulation, illustrated by the annexed figure, is then as follows:

The compound or operating magnet is first placed at the curvature of the end marked by an arrow, with its north pole towards the south, and its south pole towards the north, of the bars of the lower pair designed to be magnetized. It is then slid gradually and smoothly forward (a slight oiling being applied if needful), south pole in advance, or in the direction indicated in the figure, towards the end designed for the north pole of the lower bar, and continued across the junction of the bars in the course of the dotted line, keeping the axis of the two poles in the central line of the bar till the magnet comes round to the point at which the process commenced; it is then slid off in the direction of the arrow-shaped mark. The upper pair of bars is then removed (keeping them together), and the lower pair turned over; and the upper pair being also turned over is replaced on the top, and the process of manipulation, changing also the direction of the poles of the operating magnet, is repeated. Two complete circuits being thus made, will generally develop in the highest possible degree (if the operating magnet be sufficiently energetic) the magnetic power of the two *lower bars*, whilst the upper pair, when steel instead of iron is used, is found to be comparatively weak. Before separating the bars of either pair, those above must be lifted together directly upward; and then, if the highest capacity be designed to be elicited, a separate conductor of soft iron should be laid across the two poles of each of the lower magnets in order to sustain the power when they are separated. In this way, the several bars of a compound horseshoe magnet can be put in a condition of superior, or, rather, of the highest possible energy, by the use only of the bars of its own series used interposingly, except *one*. For, when all the bars have been magnetized till the upper *pair* only is left, the same process will serve for one of the remaining bars, provided a conductor of iron be placed across the poles, so as to leave but one of the set defective. This last, however, may be magnetized by a bent plate of iron (instead of steel) being interposed, or, by any of the usual processes, may be endued with the ordinary maximum of power.



37. Comparative gain of power in horseshoe magnets by the new process.—This result can only be decidedly represented for individual cases, as a variety of circumstances serve to modify the proportions. But the *gain* is always found considerable, often astonishingly great. The case of a small but powerful horseshoe magnet of five bars of *fine steel* may serve as an example. The bars weighed about 4,000 grains each, and altogether 2.86 pounds. The magnet was constructed on im-

proved principles, referred to further on. Magnetized by the best of the processes of manipulation heretofore known, as improved by the figure of ∞ arrangement in single series, the total lifting power of the five bars, tried separately, was 37.1 pounds; but the power obtained by "the double series process" gave 48.2 pounds. In this case, the lifting powers of the bars were, on an average, seventeen, and in one case above eighteen, times their own weight. When the five bars were combined (each sustained by separate conductors during the process of combination), this small magnet bore a load of 44.5 pounds, or about $16\frac{1}{2}$ times its own weight. Of course, the sustaining power fell considerably after the first separation of the armature or conductor.

38. Gain of power in cast-iron bars.—A set of five cast-iron bars of the horseshoe form, cast very hard, and adapted for combination, derived even more advantage from this process. The bars measured 12 inches from the curved extremity to the poles, and weighed about 5.8 pounds each. In this case, plates of soft iron of same form and size as the bars, and about one-fourth the thickness, were employed *intermediately*. By the best of other processes, four of these cast-iron bars obtain an average separate lifting power, *before* the separation of the armature, of 10.5 pounds, and a subsequent permanent power of 8.5 pounds. But, under *Scoresby's process*, the primary power was increased to 19.5 pounds, *almost doubled*, and the permanent power extended to 11.8, being almost one-half gain.

39. Scoresby's process for the magnetizing of large straight bars of steel in series.—For bars, such as those adapted for powerful magnetic machines, or for the adjustment of ships' compasses, the process is as follows: If a large quantity be on hand for magnetization, place as many as may conveniently lie on a kitchen table, or bench, in a line—say four or six in number—with a plate of iron hooping (made pretty smooth on its surfaces) of a somewhat similar width to that of the bars, of the full length of the whole series, or rather more, and about the thickness of one-twentieth of an inch, or somewhat less than that of a half-crown coin. The bars having their ends marked, to distinguish the poles, must be arranged with converse poles in connection. At either extremity of the series, or a little beyond (the end of the iron plate being supported by a lath of wood), commence the manipulation by placing the horseshoe permanent magnet with its two poles ranging (one behind the other) in the direction of the length of the bars, the one in advance being of the same denomination as that of the polarity intended to be produced in the end of the bar commenced with, and in the nearest end of each succeeding bar. Whilst the "master-magnet" will never be found strongly adhering to the iron plate, slide it smoothly, and *without any hitching*, along the whole range of the bars, keeping always the same pole in advance, until it passes completely off at the farther end. A little oil applied to the surface of the iron plate will serve for preventing any hitching in the movement, which would mar the perfection of the magnetization. Removing now, by *sliding off sideways*, the iron plate, turn

the series of bars over, so as to bring their lower surfaces upward, being careful *not to break the contact* of any two bars. The iron plate being replaced on this new surface of the steel, repeat the manipulation, of one sliding stroke of the magnet, in the same way, as to the direction of the poles and the plan of starting, as before. If the bars be thick, such as to the extent of a quarter of an inch, or more, or if they be very hard in temper, a third stroke, after again turning the series over, will be requisite, and, indeed, may generally be desirable. With good management, the whole series of bars will now be found to be magnetized, not merely to what is usually considered as *saturation*, but to an extent far beyond the power of the coercive force of the steel bars to retain. At the same time, because of the equable development of their magnetisms and freedom from consecutive poles, the bars will be found endued with a larger retentive energy than if magnetized by any of the ordinary processes. If, however, it should happen that by reason of defectiveness of the manipulation, or in the way of commencing the process, or the too small extension of the iron plate beyond the extremities of the line of bars, the extreme poles should prove weaker than the others, then the interior bars only need be taken as being strongly magnetized, and the defective bar replaced in a new series.

40. *For magnetizing plates or needles for ships' compasses, by Scoresby's process.*—With a pair of powerful bar-magnets, results completely satisfactory are produced by the process referred to (34). But where a magnet of the horseshoe form only is at hand, then, the process just described is found to be equally convenient—that is, wherever a considerable number of flat plates or needles are intended to be magnetized together. But, here, a long plate of iron is not found to be needful. It will generally suffice to employ a thin plate of 6 to 10 inches in length, and of about the thickness of a shilling.

41. *Test experiment resulting in extraordinary powers.*—A test experiment, exhibiting results in attractive force betwixt a set of twelve six-inch bars of steel, which, it is believed, had never been equaled or, probably, approached, was shown before the Physical Section of the British Association, at one of its meetings about ten or twelve years ago. The steel bars subjected to the magnetizing manipulation consisted of a series which had been constructed for determining the effects of thickness and temper on the capacity of steel for the magnetic condition. Differing, therefore, as they did, in their degrees of hardness, thickness, and mode of tempering, they were by no means so favorable for the object as otherwise they might have been. They were of the uniform length of six inches by about half an inch in breadth. Eight of them were about a quarter of an inch in thickness, or nearly so, the others were thinner, and of varying thicknesses. The magnet employed was a compound one, of the horseshoe form, weighing about eight pounds. The intermediate iron plate, in this case, was only about nine inches long, half an inch broad, and about the thickness of a shilling.

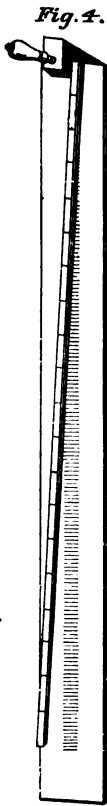
For convenience of manipulation and exhibition, twelve of these steel

bars were placed on a piece of deal board about 7 feet in length and 6 inches in breadth, along which they extended 6 feet. They were arranged in one line, commencing with the thickest bars, followed by the next in proportion of weight, and ending with the thinnest. Previous to the application of the master-magnet, the iron plate was placed, by its middle, across the two poles, so that they respectively pointed, or were directed, towards the opposite ends of the iron plate.

An extremity of the plate, so combined with the magnet, was then placed partially on the first steel bar in the series (the north pole of the magnet towards the end designed for the north pole of the bars), and gradually made to slide smoothly along, with the magnet still adhering to its middle, until (like the continuous stroke of a plane along the edge of a deal board by the carpenter) both magnet and plate passed clear off the farther end of the range of bars. The bars being now turned over whilst the continuity of the series was carefully preserved, another stroke of the magnet and iron plate, with the same pole as before in advance, was made from end to end of the series, and the magnetization was complete.

The test of the extent of development of the polarities was the power of adhesion of this extraordinary series, weighing altogether about 37 ounces, and sustained by the attractive force of a primary bar of only 2,150 grains. The second bar in the series, of about 1,700 grains, here supported above seven times its own weight, and could have held considerably more. Whilst pressing with my thumb the first of the steel bars, with a force sufficient for the support of the weight of all the others, I placed the farther end of the board on the floor of the room, which was a foot or two below the level of the platform on which I stood, and then gradually elevating the other end which I was grasping, I brought it cautiously to a vertical position, so as to leave the twelve bars to their respective powers of magnetic attraction, and to enable me to allow them all to swing clear of the surface of the board (except the one in hand), for the support of the entire chain against the force of gravitation. Two or three years ago, I remember whilst calling on a friend, a distinguished officer in the hydrographical department of the Admiralty, he mentioned to me, as a remarkable attainment in magnetization, that an American gentleman, who had just preceded me in my call, had exhibited a set of small bar-magnets which were so strong that they actually supported one another to an extent of four in a chain. My friend, who had given some attention to such matters, was not a little surprised when I told him that I could show him a dozen similar bars sustained in one chain by a process of combination and magne-

ization of my own.



42. *A chain of twenty bars, of six inches in length each, sustained by magnetic attraction.*—Surprising as are the effects of the test experiment just described, the experiment itself is not at all a difficult one. For with a set of steel bars, very defective as regards degree of hardness and due graduation of the series in thickness, a chain of twelve bars, sustained by the magnetic power developed by the new process of manipulation, may be combined magnetically with so much certainty, as to be unfailingly successful, even under the disadvantageous circumstances of a public lecture-room. But even with such defective quality of bars, the series can be carried greatly further. Thus, on more carefully proceeding with this experiment, with a further selection from my stock of six-inch steel plates, I was enabled to add no less than eight more to the magnetic chain—making, altogether, a series of *twenty* bars, extending to the entire length of *ten feet*. This astonishing chain, the plan and exhibition of which is represented in Fig. 4, was freely sustained by the mutual attraction of the bars, when the board on which they were magnetized was raised, not only up to a perpendicular position, but so far beyond it that, under the unsteadiness of the hand, produced probably by pulsation, the lower part of the chain commenced a sort of undulatory motion clear of the surface of the board, which was allowed to go on for some time, without disturbing the adhesion of the magnetic force. To witness this extraordinary result of mutually supporting power, with the serpent-like movement, as if joined by hinges, of the lower portion of the chain, was very striking.

43. *Maximum capabilities of Scoresby's process yet undetermined.*—From the result of the experiment (42), accomplished without separation of the chain of bars, it is obvious that the maximum capabilities of this new process has by no means been reached. For the securing of the best results in such a test experiment, I should procure a set of at least a dozen bars of six inches in length, and half an inch, or five-eighths in breadth, and of graduated thicknesses, from three-eighths down to one-eighth of an inch. This set I should have made of *best cast steel*, hardened thoroughly and equally from end to end, ground smooth on the surfaces, and the ends being square, carefully polished with a hone and buff-strop. A second set of about twenty bars or plates I should have prepared of best cast steel, or shear steel of the best quality, similar in length and breadth to the others, and of graduated diminishing thicknesses, from an eighth to a twentieth of an inch. This set, ground and polished like the first, should, if constructed of *cast steel*, be reduced in temper, so as through the entire length of each plate to be of similar hardness to the best cutlery; but if made of shear steel then each bar and plate should be fully hardened, according to the capabilities of this quality of metal, throughout its extent. Under such providings of bars and plates, it would hardly exceed my expectations if a chain of thirty, possibly three dozen, should be found capable of mutual suspension by this powerful process of magnetization.

It must not be supposed, however, that the extraordinary polarity thus developed can possibly be sustained by the measure of coercive force or rigidity naturally inherent in the bars. On the contrary, the magnetic development *being excessive*, a great loss of energy must take place in the whole series of bars whenever the sustaining influence of the original contact is disturbed by the breaking of the connection.

44. Anomaly in magnetization.—In certain magnetizing processes, where magnets of the **U** form, or a pair of straight-bar magnets, with opposite poles combined in near proximity, are employed, I have often found that these magnets might have a damaging effect if *too powerful*. For all processes in which the poles of straight-bar magnets are used separately, or where the opposite poles are drawn asunder from the middle of the bar, under manipulation, to the ends, the *master-magnets* cannot be too powerful. But for magnetizing with a curved or combined magnet, a series of bars or needles, forming a continuous straight line, on the plan of Michel; or a pair of bars with iron armatures, forming a parallelogram, in the manner of Du Hamel, Dr. Knight, and Coulomb; or for augmenting the developing power by Scoresby's process—the relative powers of the magnet and of the bars or plates acted on require some adjustment. This fact, which I have abundantly proved, is not as far as I am aware, publicly known. An overwhelming power in the master-magnet becomes thus, in certain cases, not only deteriorating, but sometimes almost entirely defeats the aim of magnetic development.

Thus, in the magnetizing of the series of bars employed in the test experiment (42) a single stroke of a horseshoe magnet of less than 3 pounds weight will, with a thin slip of iron placed beneath it, produce a sufficient polarity for the sustaining of the twelve bars; but if a magnet twice as powerful be made use of, the thinner bars, below, will scarcely adhere. Hence, for the attainment of higher sustaining powers I employ for the bars of three-eighths to one-eighth inch in thickness the more powerful magnet, with a tempered steel plate of about a twentieth of an inch interposed; but before pressing downward over the thinner plates, I slide the master-magnet off sideways, at the middle of the last of the thicker bars, and substitute the smaller magnet for the rest of the stroke. In this way one complete stroke on each side of the bar easily yielded a sustaining power for a chain of fifteen. Had the larger magnet, in this case, been used for the manipulation throughout, it would have been needful to interpose a thicker plate of iron or steel.

45. Highest magnetizing powers attained by electro-magnetic arrangements.—Great as the magnetizing power of induction in permanent magnets of steel is found to be, especially in those of the best construction, as combined in the *compound* form, there is yet another agency, of comparatively modern discovery, which possesses powers of magnetic development incomparably exceeding those of ordinary magnets; for the most powerful of all agencies hereto employed for the effective coercing

and developing of the latent magnetisms of iron and steel is derived from electrical sources, and especially from the influence of galvanic arrangements. A long wire of copper, or other unmagnetic metal, covered with thread or silk, like bonnet wire, being wrapped round some hard smooth ruler or roller of a cylindrical form, and in close arrangement of the coils, so as to form, when the roller (or mould) is removed, a close helix or spiral, becomes magnetic, if the ends of the wire be connected, respectively, with the two poles of any voltaic arrangement when in action—the power of the magnetic development increasing with the increase of the heliacal coil, and the energy of the galvanic battery employed. The direction of the magnetism developed in the copper wire is transverse to the length of the wire, and therefore in the case of a helix is in the direction of the axis of the helix. If a bar of iron or steel, then, be placed *within* the helix, whilst under the galvanic power, the bar being so wrapped in paper, or otherwise supported, as to be kept near the center of the cylindrical space, its magnetism will obtain high and powerful development by means of the inductive or accumulated inductive energy of the several coils of the wire around it. In this way an unlimited amount of inductive force may be obtained, adequate to the complete magnetization of the largest steel bars, and of the most resisting material or condition, required to be acted on; whilst in bars of soft iron, when formed into temporary magnets by similar arrangements and agency, an amount of attraction can be easily developed of very astonishing power. Admirably adapted, however, as this mighty agent of magnetic development is for some particular purposes, it is far less convenient for the magnetizing of plates and bars of steel ordinarily required for practical purposes than the induction of good compound magnets which can be brought into use in a moment.

CHAPTER III.

Magnetical apparatus.—Improvements in compound magnets.—Magnetic machines and compass-needles.

I.—IMPROVED COMPOUND MAGNETS.

46. *Compound artificial magnets.*—Compound magnets, having more or less fixity of polarity, are usually constructed of magnetized steel bars of similar shape and size (though sometimes made shorter, as by steps, at the sides), secured firmly together by screws or clamps, so as to produce somewhat massive and powerful instruments. The two kinds in ordinary use are those of the horseshoe, or U form, and of the straight-bar form. These combinations possess differences in amount of power, arising, not merely from the quantity of steel employed in them, but from a variety of other circumstances, which we shall have occasion to notice. Besides the convenience in bars of moderate sub-

stance or thickness, for tempering and magnetizing, other principles belonging to the development of the magnetical condition are in favor of this system of combination in preference to the construction of very massive solid magnets. But in any mode of construction, combination as well as massiveness becomes relatively deteriorating.

47. Principles of deterioration in the combining of magnetic bars.—

While the combining of bars or plates of steel in a magnetized state, by their principal flat surfaces, and with similar poles in contact, tends to yield a general result of increasing power to the magnet as a whole, a general damaging influence of the original powers of all the bars thus situated necessarily takes place; for the series of bars, requiring to be combined with the like polarities in contact, necessarily tend to reduce, destroy, and invert each other's power. And this tendency is found in practice to go to so great an extent that, in the instance of compound magnets constructed on the principles prevalent with manufacturers until a very recent period, the possibility of advantageous combination was found to be very limited. Thus, with the ordinary stout bars of common steel designed for straight-bar magnets, the union of a second bar, instead of doubling the power of either of them, would only add, perhaps, a half; the union of a third bar, about a quarter more; of a fourth, an eighth more, so that no extent of combination with such quality of magnets could, in those usually manufactured, effect more than the doubling of the power of a single bar. This fact as to compound straight-bar magnets of 12 to 15, or even 24 inches in length, with bars of about an inch in breadth, and a quarter of an inch, or less, in thickness, I verified by the trial of a considerable variety of such combinations. And, further, I found that in attempting to increase the power of compound magnets of this kind, by other additions to their substance, sometimes the total power would be diminished; and, on separating the bundle of bars, some one, if not more, would be found to have altogether lost its polarity. Magnets of this kind, both of the straight-bar and of the horseshoe form—and I have not met with anything superior until after the publication of the researches referred to below—were all constructed on the same defective principle, viz, hardened only at the ends of the bars, the rest being soft; made of those or similar massive proportions, and of the ordinary steel of commerce.

*48. Original improvements in compound magnets.—*Theoretic considerations, supported by a variety of experimental facts, led me to certain important principles of improvement, which were first published in the report of the British Association for 1836, and, subsequently, more in detail in Parts I and II of "*Magnetical Investigations*," which were issued in 1839 and 1843.* These researches showed that great advances

* It has been objected, as I am well aware, to the claim herein indicated for original improvements in magnetical instruments, that some of the principles insisted on are not new—such as the hardening of the steel bars throughout—the same principle, it is said, being pointed to or mentioned by some of the magneticians of the last century.

in magnetic energy in combined plates and bars could easily and with certainty be realized. Two leading principles—to which others for *special* cases of form or massiveness were added—were found to be of general applicability where powerful combinations are designed: (1) The employment of the finest qualities of steel, such as that, for instance, converted out of the best charcoal manufactured iron of Sweden; and (2) the hardening of the bars or plates equally throughout their length. But modifications in the degree of hardness will be needful where great masses are required to be combined, or, in certain cases, with reference to thickness in the separate bars, or to the shape into which the compound apparatus may be cast. These cases may claim some separate notices.

49. *Improvement in compound magnets of the horseshoe form.*—For compound magnets of this form, made of the best *cast steel*, I found, besides the application of the two general principles above noted, that a specific reduction of the general temperament, from that of very brittle hardness, was advantageous. The proper reduction was secured by placing the whole of the series of bars for several minutes in a bath of oil heated to about 500 degrees. When the temperature of the oil was but 300 to 400 degrees, the capacity for magnetism, in *the cases tried*, were below a maximum, and when the hardness was reduced in boiling linseed oil there was also a loss. But in the employment of *shear steel* for this form of compound magnet no reduction of the extreme hardness was needful.

Horseshoe magnets of 5, 9, and 15 bars, being thus arranged and treated, exhibited very unwonted powers. One magnet, not of the best steel, which had originally been hardened only at the ends, was subjected to general tempering to the extent, perhaps, of a hardness about equal to that of ordinary carpenters' tools, and the simple effect was to advance the *prevalent* sustaining power of the armature from about 30

In two respects, however, they were demonstrably new: (1) As the results of original investigations; and (2) as having, at all events, ceased to be acted on by modern manufacturers of magnetical apparatus. Thus, in a compound magnet in the Royal Institution, London, of the horseshoe form, by one of the most eminent foreign magneticians; in another in my own possession by a principal London instrument-maker; in *intensity*, needles, which I have examined, by a celebrated foreign philosopher, as well as in a great variety of other instruments, including a large number of compass-needles, not one was found which had the qualities essential for the best instruments, as derived from and demonstrated by my magnetical researches. So far otherwise, indeed, that on the first publication of my proposed improvements in compass-needles before the British Association, at Bristol, it was objected, by a gentleman of mathematical and scientific standing, that the principles were contrary to the results obtained by Captain Kater, published in a paper in the "Philosophical Transactions," for which the Bakerian medal was awarded. Yet, these very principles are now adopted for the naval department of the public service. Hence, if the principles of superiority contended for had, any of them, been long ago published, they were not practically carried out, or scientifically received. The hardening of magnets, if recommended, had not been proved to be essential, and the principle having become obsolete was practically repudiated or unknown.

pounds to upwards of 80 pounds. Other examples were but little less striking.

The powers elicited in the bars of three or four compound magnets of this form were highly satisfactory, many of the smaller bars, of half to three-quarters of a pound, being found capable of sustaining separately, and in the roughest manner of trial, 8 to 10 pounds or more, or from 15 to near 20 times their own weight. If these, however, had been loaded in the careful progressive manner pointed out by M. Hæcker, they would probably have sustained a very large augmentation. The famous magnets by M. Logeman (produced many years after the publication of these researches), two of which were exhibited by Sir David Brewster, at the meeting of the British Association, in Edinburgh, in 1850, derived their chief superiority from the adoption of these principles, aided, not improbably, in the larger instrument, by magnetization under the galvanic power of induction, which, in the case of massive bars, possesses a more powerful and *penetrative* action than can possibly be exerted by the mere passage of the poles of a permanent magnet across the surfaces. In the case of Logeman's horseshoe-shaped bars, however, of *light* or moderate masses—such as half a pound to a pound in weight—some of the separate bars of one of my small compound magnets were proved to be considerably more powerful, proportionally, as tried by the simple test of sustaining power in weights hastily applied, than those exhibited in Edinburgh.

50. *Scoresby's compound plate magnets.*—This designation has been applied in the catalogues of metropolitan instrument-makers to straight bars or fasciculæ of hard thin plates of cast steel magnetically combined, constructed on principles described in "Magnetical Investigations," vol. I, p. 159, viz, the employment of thin cast-steel plates (such as the busk plates of commerce), hardened in oil pretty nearly to the brittleness of glass, magnetized separately, and, ultimately, formed into two fasciculæ, the contrary polarities of the two compound bars being made by conductors of soft iron to be mutually sustaining during the process of combination and wrapping together. The theory of this construction was deduced from results of experimental research, which went to prove: (1) That, for moderately thick straight bar magnets, and for all compound straight bar magnets, superior cast steel was the best material; (2) that for any considerable degree of massiveness, even such a thickness of a fiftieth part of the length of the bar of ordinary proportions, the best temper was extreme hardness from end to end; and (3) that for all measures of massiveness or thickness, an increase of power was always obtained by dividing, so to speak, a single solid bar into slabs or plates, with a continual increase of the ultimate capacity with the increase in the number of the plates by which the dimensions and weight of the single solid bar might be made up.

51. *Extraordinary inductive powers of these thin plate magnets.*—On these principles I constructed, in the year 1838, a pair of straight bar

magnets, composed of 24 thin plates each; the plates being of cast steel, 15 inches in length, an inch and a half in breadth, and of about a thirtieth of an inch in thickness. The magnetical powers of these bars, as tested by their deviating action on a compass, time of oscillation when suspended by a thread, and, above all, by their inductive action at a distance, were altogether unexampled.

Subsequently I made a much larger combination of similar magnetized plates. Ninety-six plates were comprised in each of the fasciculæ (a slip of brown paper being interposed between every two plates), which were securely bound and kept firmly together by strong black linen tape. The ends of both magnets were ultimately ground flat and smooth. The entire bulk of each bar when finished measured 15 inches in length by $1\frac{1}{2}$ inches in breadth, and 3 inches in thickness. For convenience of use in experiments, and for practical manipulation, I had them securely fixed in a strong frame of wood, adapted for the table, with a revolving axis, permitting their being placed, at pleasure, horizontally, vertically, or at any required angle of inclination.

The powers realized justified the most sanguine expectations. Their actual magnetic energy, as measured by the sure test of inductive action, was found to exceed that of any possible combination of straight bars of the ordinary or prevalent principles of construction, of like mass and dimensions (comparing them with bars, for instance, of a third or a quarter of an inch in thickness), just about *seven times*. Besides the capability of giving inductive force to a key of a pound weight, so that, at the distance of an inch or more, it could sustain two or three other large keys in diminishing series; and besides the power of sustaining light iron or steel bodies (such as the larger kind of steel pens), against gravity with a thickness of half an inch or more of wood or glass interposed; the two compound bars, when placed a little open, with opposite poles approximated, were found capable of supporting *ten thousand* polished half-inch sprigs!

II.—MAGNETICAL MACHINES.

52. *Whether the combination of artificial magnets has, practically, any limit of power?*—From certain well-known facts, as to magnets of small dimensions being more powerful than large ones, as to the loss of power, proportionally, occasioned by combination, and as to all attempts to obtain anything like a due proportion of attractive force in large magnetic machines (until since the adoption of the principles of construction insisted on in article 48); from these and other cognate facts of experience, it might have been questioned whether some proximate limit, in the augmentation of mass or extent of combination, might not render the construction of huge machines practically nugatory? Magnetical investigations, in extensive series of experiments, pursued with this inquiry in view, enabled me to come to a satisfactory and decided conclusion, as forthwith will be seen.

53. *Determination of principles necessary for unlimited magnetic powers.*—The experimental investigations referred to above, gave, in favor of the fact of the practicability of unlimited augmentation of power in magnetical machines, these several results: (1) That magnetic bars, designed for large combinations, may be conveniently, and often advantageously, constructed of various or numerous pieces. (2.) That the separation of a long bar, say of 3 or 4 feet, into several portions, is not disadvantageous in regard to power, provided good contacts betwixt the ends of the pieces are secured. (3) That the resulting power is similar, whether, in the combination of several series of short bars, the elementary bars be of the same or of unequal lengths. (4.) That the ultimate power of any given thickness of steel in combination is increased by the employment of thin bars or plates, the due hardening of which, too, is favored by the thinness. (5.) That although magnets of large dimensions are less powerful with respect to their masses, than small ones, yet in combinations of bars into magnets of *proportional* dimensions (the quality of the steel and degree of hardness being duly attended to,) an absolute increase of power, *ad infinitum*, may be attained. But for this result, let it be remembered, that the increase in the mass of the respective magnetic combinations must not be in any one of its dimensions, specially. but equably in all; for it has been shown that the number of the bars of a compound magnet may be so multiplied in thickness as, ultimately, not only to become useless, but damaging. A proper regard, therefore, to suitable proportions of length and thickness, is essential to the attainment of the results contemplated in the present determinations. The practicability, then, of a beneficial enlargement of magnetic combinations to an unlimited extent, must involve the condition of *enlargement in proportional dimensions*. Thus, if we fix on 2 feet long by 2 inches broad, and an inch thick, as favorable proportions, then good and effective magnets may be constructed of 10 times, 100 times, or 1,000 times their several dimensions.

54. *Construction of a large and powerful magnetic machine.*—On these principles I constructed in the year 1842-'43, a magnetic machine composed of two similar parts of about 4 feet in length, the center row of bars projecting to 4 feet 4 inches, $4\frac{1}{2}$ inches in breadth, and 6 inches in depth. The two parts comprised 450 running feet of steel bars in about 380 separate pieces. Though the general arrangements and nature of the armaments were ill adapted for great lifting powers, yet 400 pounds weight was easily carried by a simple plate of iron as a conductor. If, however, the same mass of magnetic materials had been cast into a U shape, the sustaining power might probably have been extended to a ton weight. The inductive power of the machine realized every expectation. At six inches from the poles, a chain of six keys, generally of large size, was sustained, which could be then moved off to the distance of a foot without separation. With a board of nearly half an inch in thickness, interposed between the poles and the conductor, a weight of

15 pounds was sustained. A bar of soft steel, six inches long, half an inch broad, and a sixteenth thick, was magnetized to saturation, by one transit or stroke across a single pole, *through a block of wood two inches in thickness*—becoming so powerful that it carried large polished nails weighing from 600 to 822 grains. *A compass was largely moved by the changing of the direction of the poles of the two magnets, through walls and other interposing substances, at the distance of 100 feet; and sensible movement might have been given 300 feet off.* When fitted up with an armature and other apparatus, for electro-magnetic purposes, in which I was specially assisted by Mr. James P. Joule, F.R.S., it was found capable of decomposing water, and of electro-plating polished metal, *very rapidly*; and when worked by a galvanic battery of four tall cylinders, if exerted at one end only, a power of about a twelfth part of that of a horse. But none of the capabilities of the machine have yet been fully developed.

From the results of this experiment, taken in connection with the principles on which the machine is dependent for power, it is evident that a magnetic machine, or separate *compound beam* of magnetic force, might easily be constructed of the size of the mainmast of a line-of-battle ship, *the power of which, acting deflectingly on a compass, would be sufficient to produce a disturbance at the distance of a mile.* It is, moreover, abundantly evident, that a monster machine, if required for any appropriate chemical or mechanical purpose, might be constructed of hard plates of *cast iron*, so as, with the attainment of enormous powers, to come within no extravagant amount of cost.

III.—COMPASS NEEDLES.

55. *Experimental needle; original improvements.*—Two distinctive qualities were obviously to be aimed at, for the obtaining of the most effective needles for the directing of ships' compasses: (1) The attainment of the greatest magnetic energy or *directive force* of which a needle of suitable size and weight might be susceptible; and, (2) The securing of the greatest possible degree of fixity, or *permanency*, of the originally-elicited power. The principles on which these desiderata depend were largely investigated in experiments made more than twenty years ago. The first practical result of the researches was made public at the meeting of the British Association at Bristol, in the year 1836, by the exhibition and description of a new compound bar or needle, suspended on a pivot, and adapted, when constructed on a suitable scale, for the construction of very superior needles for ships' compasses.

This experimental bar consisted of four thin plates of cast steel, tempered or hardened equably from end to end, which were placed nearly parallel to each other, rather closer at the ends, but not in contact, spaces of about a quarter of an inch, by which a higher degree of power was secured, being produced by the interposition of discs of wood betwixt the several plates. For convenience of construction, the plates were

pierced, correspondingly, with five small holes, one near each extremity, and two, an inch and a half apart, near the center. Small brass pins passing through the several sets of holes and through the intermediate pieces of wood, afforded, by screw-nuts at the points, the means of ready and secure combination. The needle, as thus made up, was fitted with an agate and pivot, and also with the means of suspension by silk fibers, so as to traverse edge upward. The gain of power over any previous instrument of corresponding dimensions and weight was found to be great and decided, with a still more unusual permanency of the magnetic energy.

56. General character of compass needles previously in use.—Previous to the time of the construction of the instrument just described, the needles in ordinary use, both in the royal and mercantile navies, were excessively defective in qualities the most important for the real effectiveness and durability of action of the compass. They were generally weak and unenduring, whilst those supplied for the Royal Navy were, I believe, amongst the worst of their kind. I had tried and tested (about this period of time) a very considerable number of compass needles, by various makers; few were moderately good; not a few were *intolerably bad*. Nine needles were furnished me by the late Captain Johnson, R. N., in 1839, as fair specimens of those then in use in the Navy; some of these as to mere directive force were tolerable of their kind; two out of four, by one of the accredited makers for the Admiralty, were utterly incapable of performing their intended function. Compared with needles constructed on the principles described above, all those which I had an opportunity of trying were singularly inferior. Weight for weight (compared with needles of similar length), my compound edge-plate needles exceeded the others in the proportion of about $2\frac{1}{2}$ to 1, in the best of those supplied to me as specimens, and about 5 to 1, in the worst; whilst as to *fixity of power*, the superiority of mine scarcely admitted of a comparison. For under the action of a very trying and damaging test (article 59), which my needles could sustain with so trifling a loss as to leave them still in possession of above double the power of which any of the others were susceptible—the others lost, without exception, the entirety of their original polarity.

57. General quality and defects of the needles at present supplied.—The compasses now in prevalent use in the mercantile navy, whilst greatly improved in their general character, finish, and effectiveness, yet remain, so far as I may judge from a considerable number recently examined, *far behind* what they should be. In a recent trial of several compasses, accidentally gathered together, at one of our principal sea-ports, I found the old-fashioned principle of tempering the *ends* of the needles only, with no decided regard to quality or denomination of the steel, prevalent in the whole series, except in one by an Admiralty maker. They were all, of course, inferior to what they might be. The best had scarcely half the power of one of my four or six plate needles

of corresponding weight, and one of the worst, *not a fourth*. And when subjected to the test for *permanency*, the best yielded up nearly two-thirds of its magnetism, and the others *the whole*. After the same severity of testing, one of my own needles, weighing only 600 grains, lifted a key of 6 to 7 ounces in weight!

It should be noted that the compasses of the Royal Navy, which, before the year 1836 were characteristically among the worst in use, are now as decidedly the best. The principles which I have described as working so admirably towards the improvement of magnets and magnetical combinations are now generally adopted in the construction of compasses for ships in the public service. The "Admiralty Compasses" have their directing magnets in the form of thin steel plates (two to four in combination) hardened throughout, and set on edge, and arranged in parallel series, generally two combinations of plates on each side of center, I believe, beneath the card. The best description of these are powerful, effective, permanent, and admirable instruments, and care is now taken, I doubt not, that the whole of the varieties supplied for the public service are good instruments. Indeed the tests I have referred to are so simple and so certain, and the principles on which the best capabilities are to be secured so specific, that there is no more excuse for sending out a bad compass needle (as we shall immediately see) than for issuing a sovereign of inferior or bad gold from the mint.

58. *The testing of compass needles*.—The two principal qualities to be sought in the construction of compass needles, as I have stated, are *directive energy*, and *tenaciousness* or *permanency* in the communicated polarity.

(1) *For the testing of the comparative directive powers*.—This is conclusively effected by observing their respective action on a delicate compass when they are placed, in succession, in the line of the east or west point, and at the distance of, say, *two lengths* of the bars from the center of the compass. The *tangents* of the *deviations* produced (subject to a slight correction for extreme accuracy) are proportional to the directive powers of the several bars. If the deflecting bars are in the line at right angles to the deflected bars, then the directive powers are as the *sines* of the deflections produced.

(2) *The testing for permanency or tenaciousness*.—For this object, I have suggested two easy and effective processes. As to one of these—designed for the testing of the permanency or tenaciousness of the several bars or plates of compound magnets, or of any series of magnetic bars of similar size and form, it may be sufficient, here, to refer to "Magnetical Investigations," Volume 1, pages 36 and 116, &c., where ample descriptions of the process and its results are given. But the other, as of much practical availableness for testing the quality of compass needles, may deserve more special consideration.

59. *The test magnet for the determination of magnetic permanency*.—The *test magnet* for this process should be constructed of somewhat similar

dimensions, as to length and breadth, to the needles to be tested, and of the thickness of about half an inch. The best *cast steel* of cutlery is here required, with a hardening to its utmost capability, and a high degree of magnetization. For needles, of six inches in length, my test-bar consists of a square prism of six inches by half an inch. It is extremely hard and has a deviating action on the compass at two lengths, or 12 inches distance, of about 38° . For longer needles, from 7 to 10 inches, whilst the length of the test magnet is made correspondent to that of the needles, or nearly so, the breadth adopted is usually three quarters of an inch, and the thickness half an inch.

60. *The theory and results of action of the test magnet.*—The principle of the test-bar is founded on the general fact of the deteriorating influence of magnets placed with similar polarities in contact. Employing a test-bar of commanding power, and by reason of its extreme hardness, insusceptible of material reduction by the influence of comparatively feeble magnetic violence, the damage by unfavorable contact is sustained only (or mainly) by the needles subjected to the test. The testing of any needle or set of needles is thus effected: 1. After being fully magnetized, each needle (being marked or numbered) is placed in succession near the compass for the trial of its deviation action, and a record taken of this original directive power. It is then laid carefully down flat on the test-bar, so as to avoid any rubbing with like poles in contact, and moderately pressed down with the fingers. It is then lifted up, turned over, and replaced on the bar, pressed down as before, and being removed the operation is complete. The state of the various needles after the process is accurately indicated by their residual deviations on the compass; and their relative qualities as to fixity or tenaciousness of the magnetic power is conclusively shown. In this way a set of needles can be so satisfactorily tested, that the *best*, and the *next* in superiority, down to the *worst*, can be picked out with unfailing accuracy. Of the needles in ordinary use a few years ago, hardly one that I ever met with could bear the power of the test-bar without almost an entire loss of polarity, while some actually suffered an inversion of the poles! Where, however, any or most of the following principles have been adopted, the permanency is found correspondingly improved.

61. *Requirements for the best needles.*—The improvements in the principle of construction of needles for the direction of ships' compasses, comprise, essentially, the following particulars: (1) The employment of *cast-steel*, "converted" out of the best qualities of foreign iron, or "*shear-steel*" of like quality, if for light needles, may yield a stronger original power. (2) The adoption of the compound principle, in which 2, 4, or more thin plates are combined, the whole making up the weight considered desirable for the purpose designed. (3) The plates to be hardened equably throughout, and placed edgewise, in one or more sets, beneath the card, in true axial parallelism with the north and south line. (4) In the use of a single set of plates, on my originally suggested plan, 2, 4, or 6 plates are placed in proximate parallelism, with moder-

ate spaces betwixt them, and with a sufficient space in the middle for the pivot and its free action on the agate center. (5) On the plan as modified in the Admiralty compasses (as I have noted above) two to four sets of thin hard plates, each set having its plates in close contact, are employed.

Employing two separate combinations of plates, say, of two to four thin plates in each, and these being distributed after the manner of a two-bar compass card—now extensively employed in the mercantile navy—a very large augmentation of directive power is gained, with a permanency sufficient, with fair dealing, to last for years.

The needles which I first arranged on the compound plan, consisting of 2, 4, or 6 plates on edge, were spaced and combined by means of disks or blocks of wood, and thin screw-pins, exactly in the manner of the original experimental needle 55. Two of these, one of four and the other of two plates, were transmitted to the "Compass Committee" of the navy board, in the year 1838 or 1839. Besides these a needle of two plates, which weighed, with its own fittings, only about 400 grains, was adjusted to a *very light card* of an azimuth compass sent down to me to Exeter about the same period. It was designed for use under great stillness, and its susceptibility of action was such that when the instrument was placed on a table in *perfect repose* of everything around, the card could be seen to oscillate down to the small angular extent of the breadth of a horse hair.

62. *Permanency of Scoresby's compound needles tested.*—Defect in permanency of these needles was intimated by one of the compass committee, on an occasion when I was present at a special meeting. It was stated that the needles described above, and which had been in the hands of the committee a few weeks, had been found rather weak, as to permanency, a loss of 10 per cent. of the original power having already taken place. Such a result, I confidently affirmed, could not possibly have taken place unless the pair of needles, which were packed with converse poles connected by armatures of soft iron in the same box, had been put into unfavorable contact or proximity with each other, or some other magnet. But, at that time, I had no proof of their tenaciousness of the magnetic condition except that of the *test magnet*, which test, conclusive as on theoretic principles it seemed, might, without any fact of experience, be questioned.

Since then the tenaciousness or fixity of these needles has been amply proved. A thin *six-plate* needle, six inches long, having about double the power of any needle I had met with of similar length and weight, and a *four-plate* needle, of 579 grains weight, much stronger than the other, were put together in a small case in July, 1838. After about 16 years they were tested (meanwhile having been frequently removed from the case and handled and examined separately), when the first was found to have lost only 6.6 per cent. of its original power, and the other less than 6 per cent.

Another needle of four plates, six inches in-length, was magnetized, attached to a card in February, 1839, and being tested as to its directive power, placed in a box *quite unprotected and unsustained*. This box, though very shallow and small, was taken no special care of, being put, from time to time, into different cabinets or other places, exposed to various magnetic influences from apparatus lying about, and occasionally removed from the box. In May, 1841, the needle, being examined, and its directive power carefully taken, was found singularly powerful. It was re-examined in the beginning of the year 1855—nearly *fourteen years* after the second and special testing—when it was found to have only lost, in that long interval of time, 7.5 per cent., or about a fifteenth part of its original power, and was yet of more than double the energy of the compass needles in ordinary use! Several separate plates were also tested for the effects of time and position, and the results were equally satisfactory.

63. On the storing or keeping of spare compass cards or magnets.—Familiar as the requirements for a proper keeping of spare compass cards or magnets now are, a cautionary remark may not be misplaced, especially as, when two or three spare cards happen to be taken out of their boxes together, the needles are very liable to get into damaging contact, whilst such contact, if but momentary, seems to be little thought of. But the deteriorating influence of similar poles should never, in such cases, be lost sight of; for all magnets constructed of steel suffer deterioration, in however slight a degree, by contact, or even proximity, though but for an instant, of the similar poles of other magnets; whilst contact or proximity of converse poles tends to sustain and increase the power of both magnets so situated. Hence we must be careful, in the placing of magnets or magnetic needles together, not to allow the corresponding or like poles to come at all near to each other, much less to touch or lie in contact. And as the tendency in all cases must be to damage mutually the magnetic intensity in bars of similar size and kind, this tendency, in case of one of the magnets being much more powerful than the other, may possibly go to the entire destruction of the force of the weaker.

As to the keeping of compass needles constructed on the principles laid down above, indeed, the risk of material damage by proximity or contact with other needles is very small; but, still, a judicious carefulness, especially where strong magnets are near, should always be practiced.

64. Process for strengthening the power of compass needles without removal.—In many cases where the needles of compasses have become weak, it is a matter of convenience to be able to restore their proper polarity whilst they remained affixed to their cards. With a pair of good straight bar magnets, and by the process of magnetization, article 34, this, in the case of a single central needle, or a pair of needles considerably removed, or of a compound needle similarly placed, can be

easily and effectually done. Thus placing the north end of one magnet against the central agate on the side towards the south pole of the needle, and the south end of the other on the opposite side, and drawing the magnets asunder till they come, respectively, to the extremities of the needle, and then sliding them off sidewise, a high degree of energy may be developed. If the needles be on edge, two such strokes from the center to the ends should be made on each side. If, however, there be two or more sets of plates or needles placed very near each other, say, within two or three inches, the process may not be relied on.

In the case of the needles of *pocket compasses*, where the glass is frequently plated down by the edge of the case, or of surveyors instruments, where the needles may not be very accessible, I find that full magnetic powers may be easily and promptly restored by making the passes of the magnet over the glass, and in the manner just described. For this very convenient process of magnetization, a tolerably powerful pair of straight bar magnets is requisite. With a pair of my busk-plate magnets (50) of about 24 hard plates of steel in each, the highest susceptible power of polarity may be elicited with certainty, and in a moment of time.

CHAPTER IV.

Terrestrial magnetism; its directive action on the compass and dipping needle.

I.—DIRECTIVE ACTION OF TERRESTRIAL MAGNETISM ON THE COMPASS.

65. *The directive property of the compass*, with the cause of it—familiar as the property is—may solicit some consideration. As a magnet can produce an influence developing polarity, and exerting an attractive force on a piece of iron, without being in contact or even in very close proximity, so magnets, placed apart, exert an influence mutually on each other. If placed very near to each other, with similar poles contiguous, they will tend to invert each other's polarity, and so to damage, in case of very high magnetization, their respective powers. But if one or both of them be supported like a compass needle on a point beneath, or suspended by fibers of silk, or some other flexible material, from above, they will exert, respectively, a sort of sympathetic influence, tending when one is moved to put the other in motion, or when left to their spontaneous action, to adjust themselves with certain relations of conformity of direction with each other.

66. *Illustrations of the sympathies of suspended magnets*.—The mutual sympathies, or reciprocally directive tendencies of magnets freely suspended, might be illustrated in great variety of form and arrangement.

(1.) Where *both* magnets are so suspended as to be *freely movable*, their respective sympathies may produce some curious and interesting results. Thus, if we set a substantial and well-magnetized compass needle on a

point on the table (the point of a *stout* sewing needle fixed point upward in a flat piece of wood answers very well), and hold just over it a small compass, or a small separate magnetic needle suspended by fibers of silk, or otherwise, the upper needle will so sympathize in direction with that beneath it, and so follow its motions and oscillations, that if the larger one be set a whirling on its pivot, the smaller one, in obedience to this master-power, will follow it (unless incidentally checked) to the termination of its course. In this way by employing a very strong bar-magnet as the master influence, and placing around it (but beyond the reach of its extremities when in motion) several small compass needles mounted on separate points, the whole set will be put into sympathetic action, when the central magnet oscillates or is moved round.

(2.) *For the case where one of the magnets is fixed and the other movable*, we may take this familiar example: If directly over the middle of a powerful straight bar-magnet laid flat, or horizontally, on a table, we hold rather near it a small compass, or a magnetized needle or a bit of magnetized steel wire suspended by a fine thread, the movable needle will, after a few oscillations, adjust itself in parallelism with the axis of the magnet, with its north pole towards the south pole of the magnet. And there, whilst no further movement occurs, it will remain stationary. So if, whilst the bar-magnet is so laid on the table, the compass or needle is placed on the table in the line of the magnet, the needle, if sufficiently near, will turn into the same direction (so that the two will appear in a line), with its north pole pointing to the south pole of the magnet, or its south pole to the north pole of the magnet. In this experiment, however, the compass needle will require to be brought pretty near to the extremity of the magnet, or the exact line of uniform direction will not be taken, unless the direction of the magnet happen to be north and south (magnetic)—the direction being due to another magnetic influence, that of the earth, of which we have now to speak.

67. *The directive property of the horizontal magnetic needle.*—On these sympathetic influences, and on the power of a fixed and strongly magnetic body to influence the direction of a movable magnetic needle depends the *directive* property of the compass. The earth, which is a powerfully magnetic body, here becomes the dominant or *master magnet*, to whose influences the movable or traversing needles, unless specially interfered with by other magnetic forces, yield a rigid obedience, pointing exactly as the earth's polarity solicits, and, when properly directed and undisturbed by extraneous influences, remaining stationary in such position.

68. *Apparent discrepancy of the law of attraction of opposite polarities.*—In this case, according to the universal law, the two poles of the needle must be respectively attracted by the *converse* polarities of the earth, so that the needle itself must stand in a contrary direction to that of the magnetic axis of the earth, considered as a magnet. But hence arises some confusion of expression when we speak of the north end of

the needle pointing to (as if attracted by) the north of the earth. But, however we may designate the end of the needle pointing northward, the simple fact must be that the earth's arctic attractive force is, in reality, of the contrary kind. The discrepancy of expression has obviously arisen from calling the polarity of the end which points towards the north of the needle the *northern*, without reference to, or indeed knowledge of (at the time the name was given) the cause of that direction being taken. This discrepancy of expression has led to the adoption of a variety of denominations to express the two polarities. In what follows I have deemed it the most convenient course to speak, generally, of the north and south poles of the needle, and of northern and southern polarity in their popular meaning; but in speaking of *terrestrial magnetism*, where ambiguity might be caused by the use of these terms, the denominations *arctic* and *antarctic* (in preference to boreal and austral, which have, in reality, the same meaning as northern and southern) are used.

II.—THE DIP OF THE NEEDLE.

69. *The dip or inclination of the magnetic needle.*—Though the compass needle acted upon by the earth's directive force moves in a *horizontal* plane, such position being required for the more convenient use of the instrument, this horizontal position does not represent the true direction of the earth's magnetic force. If a magnetic needle be so suspended as to be capable of freely assuming *any* position, it will generally be found to have an *inclination* to the horizon, one of its poles being depressed, or *dipping* below the horizontal position, by an amount which is called "dip" or "inclination." The *dipping needle*—the instrument by which the true direction of the earth's magnetic force is measured—shows that in *our* hemisphere, generally, the *north* end of the needle dips, and that to an extent generally increasing from the equatorial regions northward, until, after entering the arctic circle, and in a position near to the wintering place of the late Sir John Ross, in his adventurous voyage in 1829–1833, the magnetic needle is found to stand in a vertical position.

70. *Terrestrial magnetic poles.*—The position—where all the forces of terrestrial magnetism are so combined as to attract a correctly suspended and freely moving dipping needle in a direction directly downward, and where the ordinary compass needle would necessarily cease to traverse—is considered as a *magnetic pole* of the earth. So, in correspondency with the terms in common use with respect to geographical latitude, the places where the dipping needle is horizontal, having no inclination, are considered as being in the *magnetic equator*: and the degrees of the needle's inclination are taken as *degrees of magnetic latitude*, and denominated north or south, according as the northern or southern pole of the needle is depressed.

71. *Irregularity, geographically considered, of the terrestrial magnetic equator and lines of equal dip.*—The inclination, or dip, which, as a gen-

eral rule, is northerly in the *arctic* hemisphere, and southerly in the *antarctic*, changes, with change of latitude, very irregularly, the magnetic equator forming a waving line intersecting and crossing the equator of the earth. Thus, whilst in the longitude of 30° W. the magnetic equator is in about 16° *south* latitude; on the western coast of Africa, close to the land, it rises, up to the Gulf of Guinea, to the northward of the line.

Like irregularities, comparing magnetic with geographical latitudes, are found to occur in the course of the lines of equal inclination. Thus, sailing from the Bristol Channel towards the S. W., or S. W. by W., we might have the *same* dip of about 70° for 1,800 miles. Or, still more remarkably, we should find that, pursuing a similar southwesterly course from the Cape of Good Hope, with a dip, at starting, of about 52° , we might proceed for a distance of 2,500 miles with but little alteration. But, on the other hand, sailing from Cape Horn, or from the southern part of New Zealand, on the same course, we might increase the southerly dip from 10° to 12° , in a distance of 1,000 miles; or, in some positions and directions we might, within the same distance, find twice that amount of change in the inclination of the needle.

III.—VARIATION OF THE NEEDLE.

• 72. *The variation or declination of the compass.*—There is another peculiarity in the direction taken by a freely suspended magnetic needle, which, however familiar to the sailor and others, it may not be unfitting to notice, that is the “declination,” or “variation of the compass.” The direction of the compass needle constrained to move in a horizontal plane, as is well known, by no means coincides with the true north on the surface of the earth; and this want of coincidence, or “variation,” changes in amount and direction as we change our position on the earth’s surface. In England the deflection is from 22° to 28° towards the west; in other countries and regions of the globe it varies, in some it being easterly, and in others westerly, to every possible extent.

73. *Secular changes of the variation.*—The variation of the compass, fixed as for limited periods it may appear to be for any given places, is, in reality, subject to continued secular changes; not only to changes of a tolerably uniform character from year to year, but with a fluctuating motion perceptible with delicate instruments, from hour to hour in the day, and from month to month in the year. The *daily changes* are too minute for ordinary observation. The *annual changes*, too, are so small as not to produce any practical inconvenience to the navigator, except after a period of some years, and as the progress of change has, in very many cases, been pretty well ascertained, the careful navigator or scientific observer may easily apply the requisite correction.

IV.—TERRESTRIAL MAGNETIC FORCE.

74. *Differences in the terrestrial force.*—The great magnetic body, the Earth—like other magnets—possesses different degrees of force or en-

ergy in different parts. Generally the total force is the weakest about, or near to, the region of the magnetic equator, increasing in power as we proceed northward or southward towards the places of the magnetic poles. The extreme differences are such that in some parts of the globe the total magnetic force has upwards of twice the intensity of the force in other parts; or, more accurately, perhaps, the greatest and least forces may be represented by the proportions of about 10 to 21 or 22. This is the force which acts upon the dipping needle.

75. Processes for determining the amount of the earth's magnetic force.—The relative amount of the earth's magnetic force in various regions may be determined by at least three or four methods of experiment.

(1) *By the times of oscillation of the dipping needle.*—The most familiar and easiest of these is by the oscillations of a dipping needle, the oscillations being the quickest where the force is the greatest, and the force being proportionate to the square of the number of vibrations in a given time of the same needle, supposing its magnetic power to remain unchanged.

(2) *Other methods of determining the terrestrial force.*—The differences in the magnetic force of the earth may be determined by other methods, such as by observing the deflections of a dipping needle caused by a given small weight, or by observing the weight which will cause a given deflection (90°) in a given dipping needle; or by observing the times of oscillation of a horizontal needle in different regions where the dip is known. The same thing, too, might be equally well and much more rapidly done by having a dipping needle so constructed as to admit of a small permanent magnet (of highest fixity) being placed at right angles to the direction taken by the dipping needle, and easily adjusted to the same precise distance from its center or axis; by means of which, on observing the exact measure of the angular deflection from the proper inclination, we should have, in the sines of the deflections, a comparative measure of the terrestrial force in the different places where observations might be made.

76. On certain important practical consequences of the varieties in the dip and force.—On the varieties in the dip and force, just elucidated, are dependent many important consequences and phenomena in the action of the compass, and in the magnetism of iron ships, which, hereafter, we shall have occasion to bring before the reader, and of which it is desirable that persons engaged in the practical duties of navigating iron ships should have a clear understanding. Here it is only necessary to explain the effect of the terrestrial dip and force on the directive action of the horizontal needle, or the needle of the mariner's compass.

The power by which the horizontal needle is directed into its proper position must obviously have essential relation to the directness or obliquity of action of the terrestrial attractions. Where there is *no dip* the directive influence of a given magnetic force is the greatest, and where the dip is 90° , or where the earth's force acts vertically, there can be no directing influence at all. The great sluggishness of action of

the compass in high magnetic latitudes, generally, is a fact with which every arctic navigator is familiar, whilst the extreme case of *no* directive action under dips nearly approaching to 90° is a fact of observation which the explorers of Barrow Strait, Regent's Inlet, and the adjacent regions on the west of the land of Boothia of Sir John Ross, have repeatedly observed and recorded.

77. Principles regulating the directive force acting on the compass needle.—The directive power of terrestrial magnetism on the horizontal needle, or the compass, in the various regions of the globe, if the total magnetic force of the earth were uniform, would be proportional to *the cosines of the dip*.

But as the force of the earth's magnetism is not uniform, but varies, as we have seen, in its probable extreme limits in the proportion of about 1 to 2.2, the simple ratio of the cosines of the dip requires to be combined with that of the magnetic force, in order to determine for any particular places the real directive energy exerted on the needle of the compass. In other words, the horizontal force of the earth's magnetism at any place is proportional to the total force multiplied by the cosine of the dip.

78. Examples :

Place.	Dip.	Nat. cosine.	Total force.	Horizontal force.
Liverpool	71	0.326	15.5	5.05
Gibraltar	60	0.500	14	7.00
Bahia	0	1.000	10	10.00

CHAPTER V.

Terrestrial magnetism, as to its inductive effects on iron, with the augmentation of the polarity thus elicited by mechanical action.

79. Inductive action of terrestrial magnetism on iron.—In the same way in which iron exposed to the influence of an artificial magnet becomes magnetic by induction, so iron exposed, as all iron must be, to the influence of the great natural magnet, the earth, becomes magnetic by induction.

80. Terrestrial magnetic induction may be thus exhibited.—Take a bar of malleable iron of two or three feet in length—a full-sized *kitchen* poker (not a *steeled* one) will answer very well—and, holding it upright, hold a small magnetized needle, or pocket compass, near its upper end. In England the north pole of the compass will be strongly *attracted* by it, and the south pole by its lower end. This shows that the upper end of the iron bar has southern polarity; the lower end, northern. Now, reverse the position of the poker, placing it upright as before, but with its point upward. Being again tested by the compass (supposing the poker to be free from retentive magnetism in itself), it will appear that the point of the poker now upward has changed the character of its

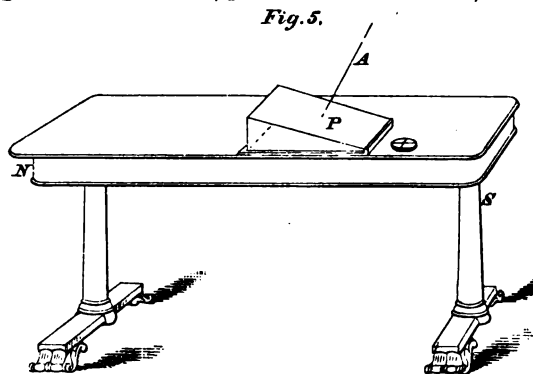
magnetism, and exhibits southern polarity, and the knob end northern polarity. These changes show that the magnetism of the poker was not a special or abiding power in it, as in a permanent magnet, but a transient influence, dependent on its position. In pursuing the experiment we find that the magnetism developed in the poker or bar is greatest, not when the bar is held vertically, but when it is held in the direction of the dipping needle. Its magnetism diminishes as its direction is inclined to that of the dipping needle, being proportionate to the cosines of that inclination, and vanishes when its direction is at right angles to that of the dipping needle.

It will be easily seen to follow from this that when a horizontal bar is held in an east and west (magnetic) position, it will have no induced magnetism; that when held in a north and south magnetic position, it will have an amount of induced magnetism equal to that which it has when held in the direction of the dip, diminished in the ratio of the cosine of the dip : 1. When the horizontal bar is held in any intermediate position its induced magnetism will be found by diminishing its magnetism when held north and south, in the proportion of the cosine of the angle between its direction and the magnetic meridian.

81. *Illustration of the plane of neutrality, or that of the magnetic equator.*—A clear understanding of the position and principle of adjustment of the neutral plane in the earth's inductive action being necessary for obtaining correct information from many of the matters investigated on my recent voyage, I shall transfer from the work before referred to* another illustration relating to the polar and equatorial directions of terrestrial magnetism for its inductive action.

For this illustration, a thin quarto or folio volume—I prefer a music book—two bits of wire, or wooden skewers, about $3\frac{1}{2}$ inches long, a straight rod or stick, and a common table, of a square or oblong form, constitute the requisite apparatus. First, place the table so as to bring one of its square sides in the line of the magnetic meridian. Then on either of the sides running north and south, place the music book, with its opening edge towards

the north, and its ends parallel to, or coincident with, the eastern or western side of the table. Raise now the upper board of the volume, and prop it up by the two wires or skewers (which should be pointed) set near the edge, or, to speak more accurately, at 10 inches distance from the hinge of the book.



* "Magnetical Investigations," vol. ii, p. 26.

Thus arranged (as in Fig. 5), the hinge and front edges of the boards will lie horizontally in an east and west (magnetic) direction; and the plane of the upper board, P, will lie at an inclination of about 20° to the horizontal level, rising towards the north, N, so as to represent the plane of neutrality, or no-attraction. Parallel to this sloping plane, therefore, or laid flat upon it, the iron bar, *if thoroughly demagnetized*, will exhibit a condition of neutrality, and so have no effect, or no material effect, on a compass placed near it, no matter in what direction as to the points of the compass it may lie. This plane being in all regions of the earth adjusted at right angles to the direction of the dipping needle will show, in each case, *the plane of the magnetic equator*, or rather the equatorial plane of the terrestrial magnetism at the place of experiment.

82. The direction, in its action, of terrestrial induction is similar in all forms of iron.—The laws of terrestrial induction, as regards the direction of the polar axis, and the position of the neutral or equatorial plane, apply, under necessary modifications, to all other forms of iron bodies, as well as to bars. These modifications arise from the reflex inductive effects of the iron itself, when magnetized by the induction of the earth. To compute these accurately exceeds the power of mathematical analysis, except in bodies of a very simple form; but an estimate sufficiently near for practical purposes can be made without any refined calculations. Hence, under the guidance of the results obtained by experiments with iron bars, I had long ago anticipated all the leading facts elicited by subsequent experiments on the phenomena of terrestrial induction in *plates* of iron, *solid masses*, and such huge and peculiarly constructed fabrics as those of *iron ships*. The principles of inductive action, by the earth, are found to be similar in all. Thus if an *unmagnetic plate* of iron be set upright, or nearly so, the upper *edge*, like the upper *end* of the poker, will show southern polarity, and the *lower* northern, no matter which of the edges be placed upwards; and if it be placed at right angles to the line of dip, all its previously elicited magnetism will be found to have vanished.

83. Augmentation of the influence of terrestrial induction by mechanical action.—The foregoing expositions prepare us to advance another step in the consideration of the effects and phenomena of terrestrial magnetic induction. It fell to my lot, as a first fruit of experiments undertaken in early life, to discover, in 1818-'19, that the polarity terrestrially developed in iron and soft steel might be increased, controlled, inverted, or neutralized at will, by *mechanical violence*, such as hammering, bending, twisting, folding, &c.; or even by simple vibration. This idea was suggested by the reflection, that if the simple influence of the earth's magnetism was so capable of eliciting the magnetic condition in iron, where there is always a *resistency* of the metal, especially in hard iron or steel, to such a state, that mechanical violence or vibration might assist in the overcoming of this resistency, and so render the iron suscep-

tible of higher degrees of magnetic development. And this view, as I now proceed to show, was not a mistaken one.

84. *Experimental elucidations of the effects of percussion.*—The general phenomena of percussion, or other mechanical action on iron, the laws of which have an essential and perpetual bearing on the magnetism and compass action of iron ships, may be exhibited by the following easily conducted experiments, for which no other apparatus is necessary than a pocket compass, a bar of soft iron, or iron poker, and a hammer.

(1) *Experiment on the magnetizing of an iron bar by a blow.*—Place the compass on a table and adjust it so that the needle may stand in the north and south line of the instrument. Exactly in the line of the *west* or *east* point, and about three inches distant, place one end of an unmagnetic iron bar or poker, held vertically, and notice the number of degrees by which the south pole of the needle is deflected. Now strike the poker, whilst thus in an upright position, a smart blow with the hammer (or any part of it and in any direction), and, instantly, the needle will start aside, as if by magic, so as so treble or quadruple the original deviation. By repeatedly hammering or vibrating the iron, while still held in the same position, the power may be greatly augmented. If the bar be then turned into a horizontal position, east and west, where (article 81) it was neutral, it will be found to be strongly magnetic, the end that was downward when it was struck, having northern polarity; and if it be inverted near the compass, with the contrary end downward, that end, which in the manner of the experiment referred to should have had northern polarity, will still *repel* the north end of the needle. The poker, for the time, and for a long time afterwards—if no further blow or vibration be given it—will be found to be a true magnet. But this quality of magnetism is not, and cannot be, the same in fixity as that of *permanent* magnets, but a changeable kind, as the next experiment will show.

(2) *Reversing the magnetism of the bar.*—Restore the now magnetic poker to an upright position near the compass on the table, but with the other end (the knob) downward, when, as already intimated, it will attract the *north* end of the needle by its portion of retained magnetism; then, striking it a smart blow with the hammer, the needle will be seen to fly round, as if by magic, into the opposite side of deflection, the percussion having served, *in aid of the earth's influence*, to invert the polarity and render the bar again magnetic, with the polarity reversed, in consistency with the proper tendency of terrestrial induction.

(3) *The neutralizing of magnetism in an iron bar by a blow.*—A third experiment with the same bar completes the series of mere characteristic phenomena. The object is to neutralize the polarity which has been elicited by the previous operations. For this purpose hold the bar in a horizontal position, and in the direction of the east and west points of the compass, so that it may lie in the neutral or equatorial plane. A blow or two with the hammer, when it is so situated (the bar being as-

sumed to be of soft iron), will now be found to have reduced the previous polarity to a small or inconsiderable quantity, which a little further hammering (if needed) will generally render absolutely neutral. The bar will have ceased to be a magnet.

85. Scoresby's demagnetizing process for bars or plates of iron.—On the last phenomenon we obtain the means of *demagnetizing* iron bars or plates, which, accidentally, or otherwise, may have become magnetic, and thus adapting them, by the simplest process, for the most delicate magnetical experiments. Previous to the determination of this fact, and almost up to the present time, because of prevailing ignorance of the fact, it was usual for experimenters, in demagnetizing, to place the iron plate or bar in a fire and heat it to redness, thus damaging it or destroying its polish, in order to rid it of the magnetic condition, which may in a moment be neutralized by the simple process described.

Where the existing magnetism in an iron bar or plate has been powerfully developed, its removal may require a blow or two with the *north* pole of the bar or plate upward, or rising above the equatorial magnetic plane of the earth.

86. Apparent neutrality not necessarily perfect.—It is difficult in a compendious description of magnetical principles to exhibit with sufficient clearness some of the more abstruse phenomena. Yet, because of its bearing on some peculiarities in the magnetism of iron of ships, not hitherto explained, it seems needful, here, briefly to notice this peculiar and little known fact. The phenomenon referred to is this: That though a bar or sheet of iron may indicate no action (when in the equatorial plane) on a compass needle placed near it, it may yet, possibly, have its molecular magnetisms in a state, not of neutrality, but of constraint. This is a condition to which iron that has been subjected to long and severe hammering in a particular position is liable, as also bars of steel which have been long in a high magnetic condition without change of polarity. The fact is indicated in various ways. Thus a bar-magnet of long standing and considerable power, having its polarity apparently neutralized by another magnet, will afterwards receive polarity more easily, and often much more strongly, in the original direction of the poles than in the contrary. Again, if such a magnet be but just neutralized, so as to have little or no action on a compass at a short distance whilst the bar is laid horizontally east and west, a few blows of a hammer on it will generally disturb its neutrality, and by the force of the molecular tension, elicit some of its original magnetic condition. If, again, a bar of iron which has been subjected to severe hammering with one of its ends always upward, be just neutralized by the process just described (article 84, experiment 3), a blow or two whilst it is laid exactly in the equatorial plane will restore some of its original polarity, though the terrestrial induction tends rather to neutralize it.

The general phenomenon is, that in iron, especially that which has had a high magnetic development under mechanical violence, there is

a greater readiness (after apparent loss of polarity) to return to its original, than to assume a reverse polarity; so that in a bar of iron so circumstanced, whilst a single blow with the bar *wrong* way up may produce a very small measure of polarity, a similar blow, the *right* way up, may suffice to restore the characteristic polarity to three or four times that extent or more! In this peculiarity and principle we may, I hope, be able to elucidate certain phenomena in the changes in the magnetism of iron ships, hitherto passed over as inexplicable.

87. Development and change of magnetic condition by other processes of mechanical action.—Results similar to those described in No. 80, as to the development of magnetism in malleable iron, cast iron, or soft steel, may be produced, though differing, probably, in intensity or degree, by any process of mechanical violence, such as bending, twisting, straining, or by mere *vibration*, of which the following experiments may serve for examples and illustration:

(1) *To magnetize a slip of iron by vibration or bending.*—Take a slip of thin plate-iron, about the thickness of a shilling, say 15 to 18 inches long and 2 inches broad; and to free it from accidental magnetism strike it a blow, or bend it slightly in the hand, whilst being held horizontally east and west. Now, whilst being held by one hand in a *vertical position*, strike it with the hand, or give it a moderate bend or twist, or shake it; then bringing it near a small pocket compass or needle it will be found to have acquired considerable magnetic power; the upper end (which should be marked) attracting the north pole of the needle.

(2) *For the reversing of the polarity.*—Strike or shake the plate again, but with the marked end downward, and the polarity will be reversed.

(3) *For neutralizing the polarity.*—Finally, strike or vibrate the plate in a horizontal position, pointing east and west by compass, and the power will be destroyed. Few experiments in natural science, so simply managed as this is, are so startling, apparently mysterious, or interesting.

88. Retentive magnetism.—The quality or character of the magnetism thus elicited by mechanical action, is, as it will be observed, very different from the qualities or denominations previously known or described—viz, *inductive* and *permanent*. The *inductive*, as we have seen, is transient, variable, or evanescent, with reference to change of position; the *permanent*, such as that in the lodestone and in hard steel magnets, is not affected, or only in a very slight degree, by position, or ordinary mechanical action; but the other, whilst variable and changeable by mechanical action, under the fitting alterations of position, may be *retained*, if the bars so magnetized be kept in a quiescent state, for long periods of time, and even under great changes of position in relation to that of the polar force of the earth. Hence, for this quality of magnetism, I have suggested the name of *retentive*.

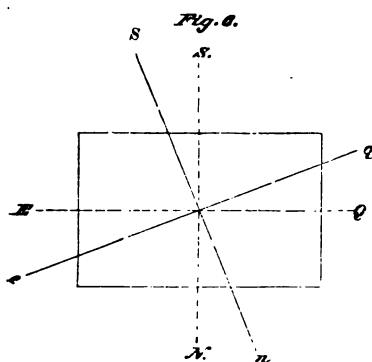
89. Important bearing of the foregoing experiments on magnetism of iron ships.—The discoveries thus far described, in respect to the phenomena of *retentive* magnetism as developed in iron by mechanical action, and which originally were looked upon by many as were scientific curiosities,

have, in recent times, turned out to be of vast importance in their bearing on the phenomena of magnetism in iron ships, and in pointing out the true theory and principles of its development, distribution, and changes. How they apply to this important subject, so essentially influencing the action of the compass on board such ships, and regulating its changes, will soon be seen; but before proceeding to that exposition it will be advantageous to our object to show the applicability of the principles so powerfully affecting the magnetism of iron bars, or slips of iron plates to sheets of iron, as well as to continuations of sheets of iron somewhat analogous to the "plating" of iron ships.

90. *The magnetical results of terrestrial induction with mechanical action on iron plates.*—In the case of slender bars of iron we had to deal only with the character of the magnetism as *longitudinally* elicited, the whole, of either end, from the middle, being endued, according to the position and inclination of the bar, with the same polarity. But in the case of sheets of iron, such as those used for iron ships, the effects of terrestrial induction, along with mechanical action, whilst following the same laws, are necessarily more complex in their phenomena. Yet with the help of the former diagrams, especially of Fig. 5, these phenomena, I hope, as to their general nature, will be easily understood, and the more so, perhaps, by the describing here of certain illustrative experiments.

(1) *Experimental illustration of the magnetic distribution in iron plates.*—Take a plate of sheet iron of a square or oblong form, and of any convenient size and thickness, so as not to be smaller than a quarto or folio book board. A *strong* sheet of tinned iron, of the kind employed by tin-plate workers may do. But it must be free from actual magnetism, which will be shown by its having no action on a very small magnetic needle placed *near* to its several edges whilst the plate is laid in a position corresponding with that of the magnetic equatorial plane (Fig 5). If it be found to be magnetic my process of neutralizing such plates, as subsequently described (92), will easily correct it.

Place the plate upright, with any one of its edges resting on the table, and in the line or direction of the *magnetic meridian*. The upper edge, from end to end, will be found, on both sides of it, to attract the *north* pole of the needle, showing that it has received southern polarity in-



ductively from the earth. The edge resting on the table will exhibit the converse, or northern polarity. Somewhere, then, intermediate betwixt the top and bottom, there must be a neutral position, the level of which will easily be found by gradually raising the compass from the table till, at an inch or two distance, the needle stands parallel with the side of the plate. But this neutral place will be found at a different level in the two ends of the

plate, being low down at *e*, the southern end, and considerably higher at *q*, the northern. A straight line, *e q*, betwixt these two points, running through, or near, to the middle of the plate, will mark the line of the magnetic equator; and a line, *s n*, drawn at right angles to this, and also through the center of the plate (being in the same direction as that of the dipping needle), will represent the *polar axis*. By reference to Fig. 5, Number 82, we find that the line *e q* corresponds with that of the magnetic plane, and *n s* with that of the polar axis.

(2) *Direction of polar axis and equatorial plane, with the plate east and west.*—For this determination, experimentally, place the plate again on edge, in an east-and-west line, inclining the upper edge backward towards the south, so that the sides may lean in the direction of the dipping needle (or of the polar axis in Fig. 5), and now, if totally free from acquired magnetism, the equatorial plane (though not so easy to be determined) will be found running horizontally through the center of the plate in the direction of the dotted line *E Q*, the whole of the portion above it being of southern polarity, and below it northern.

(3) *Intermediate directions of the magnetic lines.*—If the lower edge of the plate be placed in any line of direction intermediate betwixt that of the magnetic meridian, and that of the east-and-west points, and the plate be set upright, the equatorial line will, of course, run intermediately, as to inclination, betwixt the largest inclination of about 20° due to a meridional position and the horizontal direction, as taken with plate in the east-and-west line.

(4) *Equatorial and neutral position of the plate.*—Returning the plate, finally, into the position in which its neutrality was first tested, that is, laying it flat in the plane of the magnetic equator (Fig. 5), all the transiently induced magnetism, with its characteristic lines, will disappear.

But these simple and transient effects of simple induction, as we shall now see, may be, in a certain degree, fixed, and rendered *retentive* by percussion or other mechanical action.

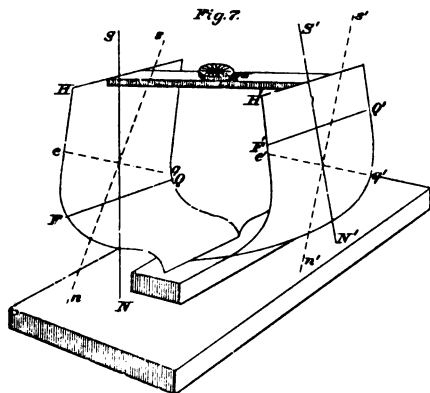
91. *The magnetic distribution in iron as augmented by percussion or other mechanical action.*—The effects of percussion, or other mechanical violence, in developing, controlling, or neutralizing *retentive magnetism* in iron plates, will be found to follow the same laws, as to the disposal of the polar axis and equatorial plane, as those just shown to prevail with respect to simple territorial induction. But the results of the phenomena are more accurate and precise, especially as to the position of the lines of neutrality, when the plate is well hammered in various directions or inclinations. Hence, whilst the polarity of the plate becomes more energetic, by reason of the retentive magnetism developed, the general line or places of neutrality will be more definite, so that, should the plate, at the first, have been in any measure magnetic, the percussion in a position steadily maintained, will hardly fail to obliterate it, and to merge it in the new and more precise magnetic distribution, or adjustment of magnetic lines. Hammering the plate the contrary way up will, as in

experiments with iron bars, reverse the polarities, and recast, into the proper direction, the equatorial or neutral line.

92. Process for the neutralization of any existing magnetism in plate iron.—The neutralizing in iron plates of any existing magnetism, either experimentally or accidentally acquired, may, as from analogy with previous experiments I had confidently inferred, be easily affected. For this demagnetization the application of the same principles as those employed for the neutralizing of iron bars is found to be equally effective; that is, by hammering, or rapping the plate pretty extensively over the surface, while placed flat in the position of the magnetic equatorial plane. By this simple process, again, not only is the method formerly practised of heating the iron to redness dispensed with, but an incomparably more ready and perfect neutralization may be obtained.

93. Application of the laws of terrestrial induction under mechanical violence to the case of iron plates of peculiar form.—An illustration, having reference to plates of a special form, will complete our designed series, and prepare the reader, I trust, for entering, with clear apprehensions of the effects of induction and mechanical action on the fabric of iron ships.

For this I employ a long plate of sheet iron—say, a foot broad and about 3 feet 6 inches in length. This may be conveniently bent into the form of the midship section of an iron ship, as represented here in Fig. 7. With an apparatus thus arranged and supported upright on a movable piece of board, the foregoing principles may be extended still further; for, here, the two sides of the bent iron (being in contact below, or at the place of the level) become mutually influential, so as, in most positions



of the model, to produce a *different level* in the lines of no-attraction on the two sides.

(1) *Experimental illustration: Head of the model towards the north.*—Thus, if the model be placed with its keel in the line of magnetic meridian, and with the edge H, considered as lying towards the *head* of the ship, towards the north, then, after due hammering over the general surface of the iron plating, we find the neutral or equatorial lines running parallel to each other on the two sides, and rising towards the head in the direction of the dotted lines *e q*; the polar axis, or place of greatest intensity at the upper edge inclining towards the stern, or in the direction *s n*.

(2) *Result with the head eastward.*—Here we have a marked change. For if the keel of the model be placed in the line of the magnet east

and west, the head H pointing *eastward*, and the surface be well tapped with a small hammer all over, we find, consistently with theory, that the lines of no-attraction now run horizontally on both sides, but at different levels—that on the starboard side being low down in the position FQ, and that on the port side much higher, as represented by the line F'Q'.

(3) *Experimental results, with the head in intermediate directions.*—If, finally, the model be turned to a side from the direction of the magnetic meridian, with the keel in any intermediate position betwixt that and the east and west, and well tapped over the surface in the new position, to render its magnetic condition conformable to that of terrestrial action, we again find an oblique equatorial line, becoming less and less inclined as the direction approaches the east and west, whilst, consistently with this change, the line of no-attraction will be the highest on the side of the model lying the most towards the north, the difference of level being the greatest of all in an east and west direction.

CHAPTER VI.

On the principles and phenomena of the magnetism in iron ships, as to its original development, direction of polar force, and equatorial plane, and subsequent changes.

94. *General laws of the magnetic condition of iron ships.*—The general laws, already stated, may be extended to the more complex form and fabric of iron ships.

95. *Summary of leading deductions on the character and distribution and liability to change of the magnetism of iron ships.*

(1) *As to the sources of the intense magnetism of iron ships.*—Ships built of iron must not only be strongly magnetic, because of the vast body of this metal which is subjected to the action of terrestrial induction, but that, by reason of the elaborate system of hammering, as well as from the bending of plates and bars during the progress of construction, there must be an *extremely high* development of the quality of *retentive magnetism*.

(2) *Effect of position of the ship when building.*—Each iron ship must have a special individuality of the magnetic distribution, depending *essentially* on the position of the keel and head whilst building, such distribution having, in each individual case, a polar axis and equatorial plane conformable to those of the earth at the place where the ship is built.

(3) *Magnetic lines of the inductive and retentive magnetism the same.*—Whilst the spontaneous influence of simple induction must be to develop a transient magnetic condition, having, in each individual case, a polar axis and equatorial plane conformable to those of the earth at the place where the ship is built; so also the retentive magnetism developed during the building must have corresponding polar direction and distribution.

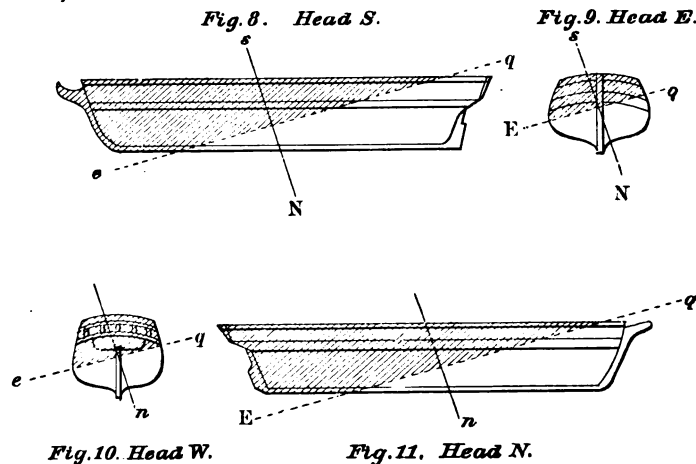
(4) *Liability of original magnetic distribution to change.*—The original distribution of the magnetism, or the casting of the magnetic lines, must be liable to change after the launching, under any violent mechanical action on the ship, when lying with her head in a new direction, or sailing in remote regions of the globe, having very different directions of the earth's magnetic force.

(5) *Sympathy of the compass with a ship's magnetic changes.*—All changes in a ship's magnetic condition must tend to produce disturbance in the action of compasses on or about the deck. And the effect must be, in however minute or insensible quantity in some particular cases, to change the amount of the original *deviations*.

How far these various inferences have been verified by recent observations and experiments will hereafter, and I hope satisfactorily, appear. Meanwhile, in our present descriptions and expositions, some verifications, of no inconsiderable importance, may be conveniently given.

96. *As to the special individuality of the magnetic distribution in iron ships.*—Here, I proceed to show more distinctly, the characteristic form which, according to deductions from experiments described, the original polar axis and equatorial plane, with the otherwise general magnetic distribution of iron ships, should take as built with their heads in various directions. The diagrams annexed, which were cut in the wood in the year 1851, and published (*Magnetical Investigations*, vol. ii, p. 269) in 1852, being some years before a single conclusive fact of experiment had been made, will serve to illustrate this important part of our subject.

(1) *The range of different cases considered.*—Suppose four vessels to be built of iron, with their heads, on the stocks, directed respectively (after the plan of the figures) to the four cardinal points of the compass, south, east, north, west.



(2) *Case with the head south.*—In the case of the first of these vessels, Fig. 8, with the head towards the *south*, the general magnetic distribu-

tion should cast the equatorial plane, or the plane dividing the northern and southern polarities, so as to rise from the keel, or fore part of the ship, near the stem, up to the deck near the stern, somewhat in the manner of the dotted line *e*, in a fore-and-aft direction, this plane being at the same level on both sides of the ship.

(4) *Cases with the head east and west, and north.*—Here, in cases of ships built with their heads towards the *east* and towards the *west*, the equatorial plane dividing the southern polarity above, from the northern below, should run obliquely across the hull, being highest on the port side with the head east, and the highest on the starboard side with the head west. And in the case of the ship's head towards the *north*, the equatorial plane should fall down to the keel abaft, rising up or above the deck forward.

(4) *Characteristic differences.*—The characteristic differences in these four cases, as derived from theoretic considerations, are rendered obvious to the eye by the straight lines passing through or near to the center of the ship in each of the diagrams; one line, *e q*, rising towards the right hand, representing the direction of the *equatorial plane*, or plane of no attraction on a compass when placed near the ship on the outside; the other, *s n*, inclining backward, at an angle of 20° from the vertical, showing the direction of the ship's magnetic *polar axis*, corresponding with the direction of the dip, or terrestrial magnetic force, as passing through the general center of gravity of the material of the ship.

(5) *Discriminating polarity.*—For convenience of discrimination, and future reference, the two polarities of the ship, as divided, proximately, by the dotted lines *e q*, are distinguished by shading one of them—the *southern* comprising in our region of the globe all *above* the line of no attraction.

(6) *General deductions on the magnetic development and intensity.*—On these principles and in such forms, varying with every difference of the line of the keel when on the stocks, should the magnetic polarities, as I considered, be arranged in iron ships; and, by reason of the immense amount of mechanical violence applied in the fixing of the various masses of iron, and the hammering in of hundreds of thousands of rivets, the *retentive magnetism* should be developed in the *highest possible degree*.

97. *The relation betwixt the ship's magnetism and the compass disturbance.*—Such relation or sympathy is a necessary consequence of the laws of magnetic action we have described. The precise quantity and form of disturbance constitutes what has been termed the "deviation of the compass," a quality of error in the compass action on shipboard common to all ships (however different in quality), whether built of wood or iron, by reason of the magnetic condition of the iron employed in the construction or fittings. In iron-built ships the disturbing action must necessarily be the greatest, and the casting of the magnetic lines the most

varied, yet, in respect to the position of each ship whilst building, the most specific. So far as the general character of the ship's magnetism goes, the ship being considered as a single united magnetic body, theoretic views seemed to guide to the conclusions just described; and of the correctness of these views, subsequent experiments on the external magnetism and equatorial lines of a considerable number of ships, have afforded (as to the leading and characteristic features) abundant demonstration. But however specific and susceptible of prediction the general magnetic condition of any iron ship, externally examined, may be, the extent and nature of the deviating influence of such magnetism within board, or on compasses placed on or near the deck, must necessarily be extremely various and uncertain. Indeed no two compasses, placed in different positions, can possibly be acted on with precisely the same measure of influence from the innumerable attracting forces of the surrounding iron; and, therefore, any compass, or rather any station or place adapted for receiving a compass, must have its own series of deviations.

98. *Determination of compass deviations by the process of "swinging the ship."*—The correct knowledge of the disturbing action of a ship on her compasses, by reason of the magnetic condition of the metallic iron used in her construction, is only to be obtained, as is well known to seamen and men of science, by the process technically designated *swinging the ship*. This process consists in determining by some convenient method of observation the compass errors (for any compass or compasses to be tested) in the various directions of the ship's head whilst she is gradually turning round so as to make a complete circuit. For this purpose, where great precision is required, the ship is usually stopped in her progress for a few moments at each rhumb, or point of the compass, to which her head is successively directed, so as to obtain a series of thirty-two observations. These, cast into a tabular form, or graphically into curves, show for any particular course to be steered the amount of the deviation, and the allowance, in way of correction to be made. But fewer observations of the compass errors than for every point will serve for all ordinary and practical purposes, such as observations for the 16 alternate points, or even for a still smaller number. Nor is it absolutely necessary to have the ship's head precisely in the direction of the rhumb to be observed, for the discrepancies can, by a practiced observer, be easily allowed for. The methods of determining the errors by the process of swinging will hereafter come before us.

99. *Endless varieties in the deviations of iron ships.*—The extent or quantity of the deviations in *iron ships*, with certain qualities in their respective series, exhibit, within noticeable limitations of analogy, an endless variety of differences. Ordinarily the errors are found to be easterly (reckoning the *deviation* of the compass according to the method employed for the *variation*) in one portion of the circuit, and westerly in another, so that in the place of transition, or "points of change," the

errors vanish, and, in these two points, the compass points to the true magnetic meridian of the earth. On each side of the points of change there is a position of maximum error (sometimes a second and minor maximum) ordinarily pretty well defined; but the two maxima, though tending to similarity, do not necessarily agree in quantity, nor do the sections of easterly and westerly deviation in iron ships necessarily take up equal shares in the circuit. In ships built of wood there is a general tendency towards the adjustment of the points of change in the north and south directions of the head, and to cast the maximum errors on or near the east and west points. But in iron ships, as theoretically we should gather from the principles we have described of their magnetic distribution, no such rule (whatever may be the shadowy tendencies) prevails. Thus we find iron ships (on comparing an extensive series) with *their points of change*, or no-deviation, ranging throughout the compass circuit. As to *the proportion of easterly and westerly* deviations we find sometimes a near equality, but in other cases 17 or 18 up to 20 points or more in one way, against 15, 14, 12, or even less, the other way. As to the relation of the two maxima deviations to each other we find a somewhat corresponding variety. And as to *the quantity of the maximum deviations*, we find, necessarily, every possible variety from a quantity so small, as scarcely to exceed what may happen to occur in some wooden ships, up to 8 or 10 points of error, if not more. Cases indeed, have been met with, from the indiscreet position selected for the steering compass, or the unfavorable distribution of the disturbing influences around it, in which, on the one side, the movement of the ship's head to an extent of a point only has produced a change of three or four points in the apparent direction as indicated by the compass; and, on the other side, the change in the ship's head to an extent of four points has been notified by the compass only as a change of a point, or a little more!

100. *How far these diversified deviations are endangering.*—The question of the effect of these various and great irregularities in the compass action and its deviations in iron ships—irregularities arising out of the variously cast and intensely disturbing influence of the ship's magnetical condition—is one of vast importance in its bearing on practical navigation. Summarily, and conditionally, we may reply, that no essential difficulty would have been found as to the compass guidance, and navigations of such ships, provided the magnetism so powerfully elicited, and the disturbances so largely and variously produced, were *permanent* or *fixed*, like that in good artificial magnets constructed of steel; for in the hands of the scientific mathematician, the compass deviations for all regions of the globe could have been pre-determined, or the original errors of the compass corrected by magnetical appliances so placed as to act antagonistically, and so correctively, against the disturbing force of the ship's iron.

101. *These diversified deviations become endangering by reason of their unfixed or changeable character.*—For the magnetism of iron ships, exerting an influence so powerful and various on the compass, as we have shown, is not a condition of fixity or permanency. And here, it may be noted, that the principles and investigations described in the foregoing pages, had long ago led me to the conclusion, that the *magnetism to be counteracted, the retentive*, which by some men most eminent in science amongst us had been deemed to be fixed or permanent, or otherwise, at least, analogous in fixity to that in ordinary steel magnets, must be liable to change, and that under much variety of conditions, and sometimes so as greatly to affect the compass, and, under certain circumstances, to change its direction very suddenly. And the conditions mainly necessary for such changes, it appeared to me, were only the application to the hull of the ship of violent or vibratory mechanical force, such as might be produced by strokes of the sea, or by hard pitching or straining in gales of wind, or even by the vibratory action of the engines in steamers, *when* the force of terrestrial magnetism might be acting in a direction different from that of the ship's then existing polar axis. The most sudden of such changes, and the largest in amount should (as pointed out by theoretic deduction) be expected to occur when the line of the dipping needle passing through the center of the ship might form the largest angle with the line of the ship's original polar axis, in a *new ship*, or with her existing or *normal* axis in a ship which has had much knocking about at sea.

102. *Theory of sudden compass changes illustrated.*—For an illustration of the nature and action of terrestrial induction in producing large or sudden compass changes, we will take the case of a new ship, built, for example, with her head towards the magnetic *east*, where, as in Fig. 9, the polar axis (representing the greatest intensity of magnetism) would lie over to the starboard side. Suppose, then, such a ship, soon after putting to sea, to encounter heavy weather, and now to have her head directed, as in Fig. 10, toward the west. Here, the new direction of the earth's polarity, now inclining to the *port* side, must obviously tend, especially under the violence of hard pitching, or straining, or heavy shocks from the waves, to alter the ship's magnetism and carry over the polar axis *n s* towards the port side. In such case, and more especially if the wind should be on the port side, so as to produce a large angle of heeling to starboard, for then the earth's influence would be still more oblique, in respect to the ship's polarities, than that of the dotted line, so as to influence the change in a more forcible degree—the shifting of the ship's polarities might be such as to occasion large, sudden, and dangerous errors in the indications of the compasses. And it is observable that these conditions were actually fulfilled in the melancholy loss of the *Tayleur*, where, on evidence that could not rationally be resisted, the compasses went astray to an extent of from two to four

points in the course of a day, or two of hard service only in battling with a southerly gale.

103. Principles connecting the changes in a ship's magnetism with compass disturbances.—The little difficulty which, in certain cases, has been experienced in the navigation of iron ships—especially of ships regularly pursuing the same voyage—had encouraged the doubt (elsewhere referred to) that has prevailed in the minds of many practical men and scientific investigators, as to whether any considerable changes, especially sudden changes in the organic magnetism of iron ships, could take place? But observation and experience—of which the voyage of the *Royal Charter* will, of itself, afford very many examples—abundantly demonstrate the fact of the prevalency of such changes in the magnetism of iron ships.

But how, it may be naturally inquired, may the changes in the ship's magnetism affect the compass so as to explain the immense variety in the results, when changes do take place, which experience indicates? Here, theoretic principles can give us but very partial guidance. They will show that all essential changes in the ship's magnetic condition (as already stated) must, unless in exceptional cases of compasses peculiarly and favorably placed, produce changes in the compass deviations, but not necessarily in such quantity or amount as to be of practical consequence, or, indeed, under ordinary inspection, observable. Yet, it is obvious that the greatest amount of change in the compasses should not only be expected to attend the greatest magnetic changes in the ship's polar axis and equatorial plane, but, generally, should be looked for in the greatest degree in compasses having originally the largest errors or deviations.

An illustration derived from further experiments with the model, Fig. 7, described in the last chapter, may here avail us towards the explanation of a particular case, from the general principles, connecting the change in a ship's magnetism with compass disturbance. And here I need to refer only to the magnetism acting athwartship. Let the figure in question represent a section of an iron ship in the place, we will suppose, where one of the compasses has been fixed. H will mark the starboard, and H' the port sides. Suppose, now, the ship's polar axis, as derived from being built in that position to lie far over towards the starboard side H, or, in other words, that this side has far stronger *southern* polarity, of the nature of *retentive* magnetism, than the other. The effect of this difference, when the ship's head lies east and west, it is obvious, would not be perceptible, because of one or other of the poles of the needle pointing directly towards the place of the most powerful or dominant influence. But let the ship's head be turned away from this position—say to the *north*—and, as now will be obvious, the two sides of the ship, possessing the same polarity, southern, will both be *attractive* of the north pole of the compass so as, if both sides were alike in force, to neutralize one another, and leave the compass correct. But,

it being understood that the retentive magnetism will be mainly unchanged in this new position of the ship's head, the assumed dominancy of the polarity of the starboard side H must also remain unchanged, the effect of which must be to draw the north pole of the needle towards that side, occasioning an *easterly deviation* with the ship's head north! Thus, let the attraction be to the extent of two points; then, with the compass showing N.NW., we should have just N., on applying the deviation in the true magnetic direction.

104. *Experimental verifications with the model.*—The above deduction from theory obtained admirable verifications from a set of experiments with the model.

(1) *On the dominancy of the upper polarity of the starboard side with the head directed towards the east.*—The model being placed in a direction at right angles to the magnetic meridian, with the edge H (the head) pointing east, and then tapped all over both sides with a small hammer, attained the condition described in art. 93, of horizontal equatorial lines on both sides, with that of the port side considerably the highest in level. And as the polar axis was thus thrown over towards the starboard side, the polarity of that side became, according to theory, more strongly magnetic than the other port side.

(2) *Effect of this dominancy of polarity on the compass with the keel of the model in the line of the magnetic meridian.*—The supporting board of the model was, in this experiment, slewed into the meridional position with the head H towards the north. In this case the magnetism of simple induction, of course, changed in correspondency with that of the earth, whilst the more fixed polarity, the *retentive*, produced by hammering with the head *east*, remained. Hence the starboard side retained, in marked and obvious measure, its magnetic dominancy. This was beautifully shown by a small compass placed on the middle of a piece of deal board fixed directly across the model, as shown in the figure. The pointing of this compass, when the keel of the model was in the true magnetic meridian, would, it is obvious, have been exactly north, provided the magnetisms of the two sides had been the same. But, according to theoretic deductions, the southern polarity of the starboard side must attract the north of the needle more strongly than the same polarity of the port side, and so draw the north pole towards the east, occasioning an *easterly deviation*. And this was precisely the result and disturbance which the compass indicated. The north pole of the needle (on the result of various experiments) was always drawn to the starboard, to the extent of from 16° to two points of *easterly deviation*.

The model, after being again well tapped over the surface with the hammer, with the head lying towards the east, was, on another trial, slewed into the direction of the magnetic south, when, as anticipated, deviations of the compass on the board pretty similar in quantity, but

of contrary denomination, were obtained. In this case the deviation was, of course, westerly.

(3) *Reverse deviations on the model being hammered with the head towards the west.*—This reversal of the deviations produced by the dominancy of the retentive magnetism being transferred to the port side, in consequence of the model, when hammered, being turned in the contrary direction, was an inevitable result of magnetic principles. But the case, as proved by experiment, is here noticed as an element in the series of experiments bearing upon the principles, now being elucidated, on the relation in a ship's magnetism with compass disturbances.

105. *Change in the dominant polarity productive of change in the compass deviations.*—Experiments with the model (Fig. 7), abundantly prove, for the special case, this general proposition; and having already discussed the theoretic principle, we have now only to add the experimental elucidations. The experiments just described show how a *dominant* polarity, on one or other side of an iron ship, must necessarily be produced during the progress of construction, whenever the keel on the stocks happens to lie in an east and west direction, or, in strict science, in any direction to the eastward or westward of the magnetic meridian. The extreme case of east and west, however, serves the best for experiments.

But, proceeding with our illustrations, we will suppose that, from any of the causes which might change the ship's polarity, the dominant power of southern magnetism should be *diminished* on the starboard side, or *transferred* to the opposite side, then the disturbing force originally drawing the north pole of the needle towards the starboard side would now either draw the less powerfully or solicit it to the opposite direction, and thus change the deviation—in one case by *reducing* its quantity and in the other by *reversing* its direction.

(1) *Experimental illustration of new deviations being obtained by changing the dominant polarity of either side.*—For elucidating this important fact we may conveniently go back to the experiment with the model, where, by hammering it with the head *easterly*, we found, on turning the head to the north (2), a deviation of the compass of near two points easterly. We now slew the model with the head *westerly*, and tap it well over the two sides with a small hammer, and then slew it, as before, towards the north. We now find a very similar quantity of deviation, but in the reverse direction, being changed from easterly to westerly.

These experiments, I think, may serve clearly to explain something of the nature of the changes to which a ship's magnetic condition must be most specially liable, and to show that a change in the deviations of any compass lying nearly in the transverse line of the dominant and minimum action of the two sides of the ship must be an inevitable consequence. On the same principle we might elucidate the natural tendency of changes in the more dominant polarity of the ship in the line

of the keel, in producing changes in the deviations, more especially with the ship's head in and proximate to the east and west points.

(2) *General experimental elucidation of changes in the deviations by mechanical action in a model in new positions.*—This tendency to change in compass deviations, under the circumstances referred to, was illustrated by experiment at the meeting of the British Association, at Liverpool, in 1854, on a plan which, from the convenience of its arrangements, it may here be useful to describe. The experiments were made with a simple and easily obtained apparatus, a dish-cover of tinned iron, and a small compass, and they stand commended for the consistent and somewhat surprising character of the results. The dish-cover was placed concave side upwards on a flat broad board, with radiating lines drawn upon its surface at angles corresponding with the eight principal points of the compass. It was attached by a pin through its center to the middle of the board where the radiating lines met, and, whilst free to revolve on this center, was kept upright and steady in its progress by an intermediate piece of wood (through which the center pin passed) scooped out to fit its convexity below. The compass, a delicate one of 3 inches diameter, was fixed on a platform of copper near to one end, so that, whilst the cover might represent the model of a ship, it might have the position, relatively, of the wheel compass near the stern.

The experiment, which was designed to illustrate the change in a ship's *original* magnetism, by straining with its head in an opposite or different direction, was as follows: The model was first placed with its head in the direction of one of the lines on the board—that of *northeast* was selected—and in that position it was struck a number of moderate strokes with a hammer on the upper sides and ends. The *retentive magnetism* thus developed and arranged was then tested by turning the head on the east and west line of the board, and noting the deviation of the compass. The model was then slewed into an opposite direction, head *southwest*, and there it was strained by the hands merely, so as, within the range of the elasticity of the metal, to press the sides, momentarily, a little outward. On returning it to the testing position, head east, the compass deviation was found to have *greatly* changed! In various repetitions of the experiment, with two different models of the same kind, the alteration (always uniform in its direction) extended generally from 10° to 20° , or, where the percussion and straining were more elaborately carried out, sometimes to full 30° ! It is difficult to imagine anything in the manner of an illustration more impressively conclusive than this experiment.

106. *Tendency of sea service to produce a normal direction of the ship's polar axis and equatorial plane.*—Theoretic deductions from the magnetic principles we have hitherto been attempting to establish and elucidate are calculated to carry us an important step farther in our anticipations of the *changes* to which the original magnetic distribution in

iron ships, after considerable sea service, should be liable. The general effect of a ship's being well knocked about at sea—that is, whilst voyaging only within the same hemisphere of the globe—should be the production of a somewhat settled medium distribution of her magnetic lines. Thus, theoretically considered, it is obvious that if the magnetic lines have a tendency, under the force of terrestrial action, to change into conformity with such action in all new positions of the ship's head; then assuming a due vibratory or straining action of the sea to have taken place with the ship's head on *all* the principal points of the compass, the ultimate result should be the production of a *horizontal* equatorial plane, and a *vertical* magnetic axis.

A large variety of facts of experience go towards the verification of this theoretic case of the *normal* magnetic distribution in iron ships, such as the gradual reduction of the ship's original deviations, the diminished liability to large or sudden changes in her magnetic condition, the improved action and reliability of the compasses, besides a variety of facts of experiment and experience.

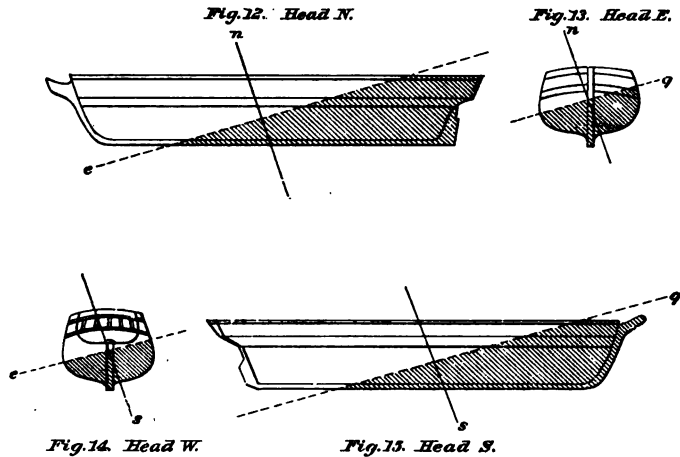
But whilst asserting these demonstrable *tendencies towards a normal result*, it is by no means assumed that the true normal condition is necessarily attained; on the contrary, as certain peculiarities in the observed phenomena appear to indicate, it is more than probable that something of the original organic magnetism is of long, possibly of perpetual, continuance, and that there is a particular *tendency* in the normal approximation to a disturbing reaction, in each case, towards the *original* oblique magnetic lines.

107. *Magnetic condition of iron ships, if built in high southerly dip, must have converse polarities.*

(1) The establishment of the theory of the original magnetism of iron ships built in England and other northern regions, as made powerful and retentive by mechanical action in process of construction, must, of course, render the principle applicable, with differences corresponding with the changes of dip and magnetic force, to similar structures raised in all other regions. The necessary result must be, that iron ships, if built at Melbourne or in Port Philip, or in any part of Tasmania, where the magnetic dip is about the converse of what it is in the Thames and more southern parts of England, must have magnetic lines running in corresponding directions, but in reverse positions of the ships' heads, with opposite polarities—the northern here being above and the southern below the equatorial or *no-attraction* plane.

(2) In like manner, if our deductions (106) as to the tendency in iron ships of the original oblique lines to fall into a medium or normal condition be correct, such iron ships, if built in Australia or Tasmania, and navigating only the seas of the southern hemisphere, should be expected to show the reverse polarities of their *normal condition*.

Thus, to repeat our illustration, we may represent such antarctic normal condition, in the form annexed.



As the magnetic lines in ships built, say, at Liverpool and at Melbourne, or about Port Philip, would, in their original casting, be symmetrical (that is, if built with their heads in contrary directions), so that *normal* condition which much knocking about at sea must tend to produce would be symmetrical as to its lines, whilst the polarities would be necessarily the reverse of each other, the upper half of the ships which in Liverpool would have southern polarity, having in Australia, as indicated by the white space in the diagrams, northern.

CHAPTER VII.

Objection suggested against the foregoing theoretic principles.—Refutation, by facts and experiments, of many of the objections, and proposal of a plan for the testing of the entire theory.

108. Introductory notice of promulgation of theory and general character of objections.—The views and principles which have been compendiously stated, being deductions from experiments, mainly on the phenomena of magnetism, as developed in its *retentive* quality, by mechanical action in iron, seemed to me when, many years ago, considering the condition and difficulties about the compass in iron ships, to point out the true theory of the ship's disturbing and varying influence, and to show something of the requirements for a sound and safe remedy. They were first publicly promulgated, and elucidated by some experiments, at the meeting of the British Association, at Oxford, in the year 1847, in a communication "On the defects and dangers arising from the use of cor-

rective magnets for local attraction in the compasses of iron-built vessels"; and shortly afterwards, in October of the same year, these views were more comprehensively set forth in a public lecture at Glasgow.

The principles, however, which, on these occasions, I had set forth, and still more elaborately in volume 2 of "*Magnetical Investigations*," published in 1852, and, furthermore, in various expositions at the meetings of the British Association, at Liverpool and Glasgow, in 1854 and 1855, &c., were, in various forms of publication, and from different quarters, objected to, denied, or even attempted to be scoffed at; for it had been previously assumed, by some other investigators, that the more intense portion of an iron ship's magnetism, which I have designated *retentive*, was of the *permanent* quality, and so not subject to any rapid alterations; that the essential condition for change was *time*, so that changes which might not improbably occur would require long periods for their being effected; and that, under certain arrangements and adjustments, the compasses might be made to act as correctly, at least, in iron ships as in others.

109. *Varieties of objections suggested to the principles here contended for.*—Out of assumptions just glanced at, as well as no small variety of others, numerous objections to my views and expositions sprung, which, from time to time have been promulgated in public journals or elsewhere.

It was stated in objections, for instance (1), that experiments with mere bars or slips of iron could not be adapted for being applied, as I had supposed, to the case of such a huge and elaborate structure, and of a form altogether so peculiar, as that of an iron ship; or (2) that the facts of experience with regard to changes in a ship's organic magnetism would not bear out my deductions. It was denied (3), on the ground of want of agreement in "compass deviations" of any two iron ships, that the distribution of magnetism elicited on the stocks could, as I had inferred, be definite and capable of anticipation; or (4) that such applications of mechanical force as ships might be exposed to at sea, would be likely to produce the effects exhibited in my experiments. It was affirmed, in objecting to my views (5), that they were those of an alarmist and theorist, and calculated to produce unnecessary distrust, if not damage, to the property of iron ships. It was denied (6) that we had any facts of experience sufficient to authorize the statement that the compass on board iron ships, at sea, might undergo rapid or sudden and considerable changes; and (7) that the action of the waves could give such decided shocks or blows to a ship as the requirements for magnetical changes seemed to demand. It was asserted, in opposition to what I had suggested, and as a supposed result of experiment (8), that the magnetism of a series of iron plates riveted together, as in ships, was not subject to the same influences as in single plates or bars. It was affirmed, in the way of refutation of my views concerning the great changes and probable inversion of the polarities of iron ships trading

into high southern latitudes, or into regions of great *southern* dip of the needle (9), that the deviations of the compasses of such ships, however they might alter, still continued of the same character as they primarily were, and so, indicated the general permanency of the original organic magnetism. In opposition, too, to my plan of a *reference compass aloft*, for the daily or constant regulation of the course at the helm, it was publicly set forth (10) that the action of such elevated compass would be so disturbed by oscillations at sea as to render it useless; (11) that the points of suspension of such compass would be rapidly damaged by the agate of the needle, so as in brief space to spoil the performance of the instrument; and (12) that, on the trial of the plan, it had, in many cases, been found to fail; and, finally (13), that Mr. Airy's adjustments could be relied on in all parts of the world.

110. *Reply to, and, in many cases, refutation of, suggested objections.*—It would not be convenient here—as it would extend much too far this introductory part of my publication—to enter, in detail, into a refutation of the various objections which have been noticed in the preceding article. But I may refer, by the way, to papers of mine in certain public journals, &c., for a record of facts, applying, as I apprehend, conclusively, to some of these, and dwell, afterwards, more descriptively, on certain characteristic observations and experiments made on board iron ships, in verification of the deductions derived from experimental investigations on the phenomena of retentive magnetism, and the principles of its changes, in iron plates and bars. Taking the guidance of the numerical affixes to the series of objections noticed above, to which the reader, who may feel interest in the subject, will be pleased to refer, we reply:

(1) That the objection to the applicability of the results of my experiments on iron plates and bars to the elucidation of the magnetical phenomena in such an elaborate structure as that of an iron ship, will be found to be answered by the facts and results, as to actual ships, recorded further on. An iron ship, though of such huge and elaborate formation, is as *unity*, magnetically considered, and the terrestrial magnetism, combined with mechanical violence, will be found to act on such a fabric on the grand system of natural laws.

(2) As to the fact of changes, sometimes rapid and considerable, in a ship's organic magnetism, and, sympathetically, in her compasses, I may refer again to the case of the *Tayleur*, involving, by the action of heavy seas, a rapid, almost sudden change in the compasses of two to four points; that of the *Ottawa*, of Liverpool, where an instantaneous change of two points was produced by the stroke of a sea; that of the *Tiber*, where a similar sudden change was produced in the compass by a collision; besides the cases of the *Canadian*, involving a still greater change in the steering compass, very quickly or suddenly produced, the *City of Philadelphia*, and others.

(3) As to the determination, theoretically, of the original character and

lines of the magnetism of iron ships whilst building, to which different writers (including one of the highest celebrity in science) have objected, we have now such an overwhelming measure of evidence as demonstrably to establish the proposition attempted to be denied. But this great fact will claim further and more particular consideration.

(4) The objection to the adequacy of the mechanical force or violence to which a ship is subjected at sea for producing rapid changes in a ship's magnetism and compass direction has already been met by the facts of the cases of the *Ottawa* and *Tayleur* (2), and will hereafter obtain out of the records of the voyage of the *Royal Charter* additional facts in reply.

(5) As to the objection to my deductions on the instability of the magnetism, and the liability to compass changes in iron ships, as being those of an alarmist and theorist, it is only needful to reply that these deductions as to the circumstances and conditions referred to will now be seen to be demonstrable facts. And if the facts be so, the supposed alarmist doctrines should result in salutary cautions and improved safety to the navigation of this class of vessels.

(6) As to the denial of their being any facts of experience to warrant the statement of occasional, rapid, or sudden changes, of any important extent, in the compass deviation in iron ships, it should be sufficient merely to refer back to our reply to objection (2).

(7) As to the denial of the capability of the waves to give violent shocks to a ship of the nature of blows, and such as to be adequate in mechanical violence to the probable production of magnetic changes, a sufficient answer (in addition to recollections by many readers of facts of experience) will, I think, be found in the subsequent records of the effects of the seas of the Indian Ocean.

(8) The objection to the applicability of my experiments on simple plates to the case of series of iron plates riveted together, on the ground of a different result from the actual trial, is founded in mistake. For, on combining numerous pieces of plate-iron, by riveting, into a slip some inches long, the same general phenomena as to the production of retentive magnetism by percussion, and its inversion by proper change of position when hammered, as resulted from similar mechanical action on simple continuous plates, were obtained.

(9) The consideration of the objection to the general principles herein set forth of the great changes, to the extent, possibly, of the inversion of the polarities, to which, under certain extreme conditions, the organic magnetism of iron ships must be liable, may be best referred to the actual facts in the magnetic changes of the *Royal Charter*, as determined at Melbourne.

(10, 11, 12) The several objections made against the desirableness of the plan of a compass aloft, for reference and general security against misguidance to the navigator, on occasion of changes or sudden disturbances in the steering-compass, will hereafter come more specially

under consideration. In this place it may suffice to say that so far as the experience of the voyage of the *Royal Charter* may afford guidance, these different forms of objection were completely and severally negatived. The plan, though by no means well carried out, was yet found entirely reliable and successful.

(13) Compasses adjusted by magnets cannot be relied on, on a change of magnetic latitude.

111. *Verification, by experiment, of the general theory of magnetic distribution in iron ships.*—The important bearing of this great fact, viz, the dependency and essential relation of the original polarities and magnetic distribution in iron ships to their respective position on the stocks, on the general phenomena of the magnetism in such ships individually its changes, and the consequent compass disturbances, claims for the particular proposition, deduced from theory, a special demonstration by reference to observation and experiment.

The correctness of the theory in the case of ships yet on the stocks I had an opportunity, first of all, of satisfactorily determining by experiment on the *Elizabeth Harrison*, of 1,400 tons (now the *Ellen Stewart*), of Liverpool, in October, 1854. The head of this ship pointed E. N. E., a position not very different from that of our Fig. 9, showing, theoretically, the course of the magnetic axis, or polar plane, and of the equatorial or neutral plane, with the head at *east*. Being provided with a ship's steering-compass, I attached it to a piece of board about three feet in length, so that the distance of its center from one end of the board was just two feet. The board was carefully slung with cords so as to be easily let down or adjusted to any level or distance from the top of the iron plating above, and the end intended to rest against the ship's side being cut square, kept the compass (in all parts of the ship's main breadth or straight side) with its lubber points in the line of the keel, and gave, without other adjustment, a uniform distance from the iron plating of two feet.

Professor Traill, the Rev. John Moss, and Mr. Towson, were witnesses of the experiments here recorded, and the descriptions are taken, in substance, from notes made by Professor Traill. Our first station was near the middle and main-breadth section of the ship. Near the gunwale, on both sides, the *north* pole of the compass was vigorously attracted. It was easy to perceive the progress of diminution of the force of attraction as the compass was gradually let down to the level of the plane of no-attraction at which the compass pointed correctly, and the change to the attraction of the *south* pole, and its rate of increase, as the compass was still further let down.

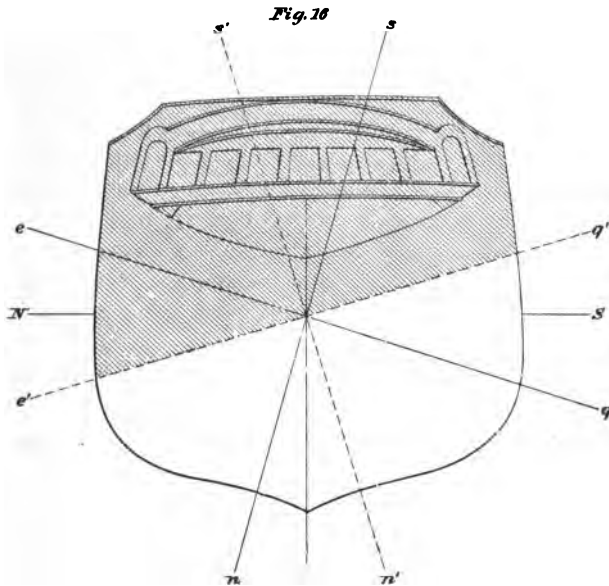
The diagram (Fig. 16), gives a stern elevation of the ship, and shows the course, theoretically, of the magnetic lines, $n s$ being the polar axis, and $e q$ the equatorial plane. Here on the actual trial, the level of the equatorial plane $e q$, as taken on both sides, was found to be 11 feet 6 inches lower down on the starboard side than on the port side, whilst

the difference of level by calculation, as previously announced to the friends who witnessed the experiment, was 11 feet. The quality of the polarity below this plane (left white) was, in accordance with theory, all northern, and that above it (shaded) southern. The ship's main breadth, it should be noted, was 36 feet 6 inches.

The annexed diagram, representing the stern elevation of an iron ship, will serve to convey more impressively to the eye the manner in which her magnetic lines were found to be cast.

Here, the section below the equatorial lines, or lines of no-attraction, left white, had northern polarity from stem to stern, and the portion above, shaded, southern. The line $s n$, running obliquely towards the starboard side, represents the magnetic axis of the main breadth section, in parallelism with the direction of the earth's magnetic force, or the position assumed by the dipping needle.

In the case of a ship built with her head towards the west, the plane of no attraction would run in the direction $e' q'$, and the white and the shaded polarities be separated by that line.



112. Further verification of the theory of the magnetic condition of iron ships.—In the instance just described, where the correctness of the theory received such beautiful verification, the trial of the ship's magnetism was only made in a few positions near the middle of the ship, so as not fully to verify previous anticipations in the rest of the ship's hull.

This lack, however, was soon supplied by further experiments, which I suggested to friends concerned in the building of iron ships, by which every prediction from theory was fulfilled, even to the *exceptions or deviations* from regularity of the lines of no-attraction which I had suggested

might probably occur where there were large or particular masses of iron inside, such as stringers, bulkheads, beams, &c. For these confirmations I was indebted chiefly to Mr. James R. Napier, of Glasgow, in experiments made on the *Fiery Cross*, the *Persia*, &c.; to Mr. R. Newell, of Newcastle, for the determination, whilst I was present, of the magnetic lines of the *Elba*, built at Jarrow, on the Tyne, with her head lying nearly *south*; and to Mr. George Palmer, for the magnetic lines of another ship built on the same site as the *Elba*. These experiments, to which others might now be added, sufficiently established the principles elucidated in articles 95, 96, &c., so as to leave no reasonable ground for persistency in objections against this important portion of the theory affirmed.

There were other results of inductive research on magnetical phenomena in iron—some of the greatest possible importance in their bearing on the great practical question of safe compass guidance in iron ships, which neither home experiments nor the information hitherto obtained respecting magnetic changes in such ships abroad were sufficient to reach, so as to establish or refute them. Nor could the extent of the operation of influences tending to the inversion of a ship's magnetism in far southern latitudes, or the extent of compass changes from circumstances adapted for producing them, be gathered from the deductions of science. If, indeed, it had been practicable to put an iron ship to the test of experiment, as in the case of iron bars and plates, so as to turn it upside down, and in that position subject it to a thorough hammering, or other mechanical action, we should then have had the asserted principles of the complete inversion of the ship's polarities by the reverse operation of terrestrial induction under mechanical action put to the test, and the truth of error of the theory in that particular satisfactorily determined.

But such, with various other forms of experiment and research, on organic changes in the magnetism of iron ships, which at home are impracticable, might be virtually made, it is obvious, by observing the effects of powerful mechanical force in straining in heavy seas, or from shocks from the waves in regions of the globe where, magnetically regarded, the ship would actually be inverted in position. The series of home-built ships which we have figured in article 96, with northern polarities below and southern above, would, if built in Tasmania, or in the southern part of Australia, where the south end of the needle dips just about as much as the north end does in England, have necessarily the reverse magnetic condition, with the southern polarities below and the northern above.

MAGNETISM.

PART III.

CHAPTER XI.

COMPASS ADJUSTMENT.

The earth itself is a huge magnet, whose magnetic poles are entirely distinct from its poles of rotation. That in the northern hemisphere is situated to the north-northwest of Hudson Bay, in British North America, and has been actually reached by man; whilst the other lies to the south of Tasmania, but, owing to impenetrable barriers of ice, has not quite been reached, but so nearly that its position was without difficulty ascertained by calculation.

Unlike the *geographical poles*, which are represented by a mere point, the *magnetic poles* include a considerable area of the earth's surface, amounting perhaps to 50 square miles.

"As the magnetism of the north end of the needle is of the opposite kind to that of the north pole of the earth, physicists are not agreed as to which should be called *north* magnetism; and it has therefore been found convenient to distinguish them by color, calling the first red, the second blue. The distinction may be easily remembered, by supposing the needle colored and from R occurring in noRth and in Red; U in soUth and in blUe."

At the north magnetic pole, the red or north end, and at the south magnetic pole, the blue or south end, of a freely-suspended needle, points vertically downwards; or, in other words, at both these places the "dip" is 90°.

Here may be stated the first general law in magnetism—namely, that *opposite poles attract*, and *similar poles repel* each other. From which it follows, that if we decide to color red that end of the needle which points to the north, the magnetism of that part of the earth must be considered as blue.

At the earth's magnetic poles all compass action ceases; since there a freely-suspended needle, pointing straight up and down, *has no horizontal force to give it direction*—hence the very apparent sluggishness of the compass in high latitudes, and its *complete uselessness* in the neighborhood of the magnetic poles. Indeed, were it not for the conical shape of the pivot and cap which compels the card of a mariner's compass to assume a horizontal position, it would tip over end as the magnetic poles were approached.

Now, if the earth has *magnetic poles*, it has also a *magnetic equator*. This magnetic equator is a sinuous curve encircling the earth, and crossing the geographical equator in two places nearly diametrically

opposite to each other, something after the fashion of the Ecliptic. One crossing is on the eastern side of the Atlantic, about the meridian of Greenwich, and the other is in the Pacific, about the longitude of 168° W. Its greatest divergence from the true equator is in Brazil, in latitude 16° S. and longitude 45° W.; its next greatest in the Arabian Sea, at a point in latitude 11° N., somewhere between Socotra and the Laccadives.

At all places on the magnetic equator a freely-suspended needle takes a true horizontal position; or, in other words, the dip is 0° . One might imagine that here would be found the strongest lines of horizontal or directive force; but most careful observations prove that such is not the case—in fact, that of the two, they rather evince a preference for the geographical equator.

To recapitulate: If a freely-suspended needle be taken to the *north* magnetic pole, its *red* end will point vertically downwards. As the needle is carried south, it will *gradually* approach a horizontal position, which will be exactly attained on the magnetic equator. Proceeding still south, its *blue* end will next begin to dip, and at the *south* magnetic pole will point vertically downwards.

The next most important point to be remembered is the difference between a magnet made of *hard steel* and one made of *soft iron*. That of hard steel will not reverse its poles, no matter at what part of the earth or in what position it may be held. Its magnetic *character* is absolutely permanent, and will so remain even though its red end be directed towards the south, and its blue end towards the north. Not so, however, with soft iron, which possesses no independent magnetism of its own. In *its* case the magnetism is of a purely transient kind, ceasing with the removal of the producing cause, and being just as easily reproduced of an opposite name.

It will be necessary to explain that a bar of *soft iron*, if held in the earth's "line of force," will *instantly* become magnetic, though it may not have been so before. Now, what *is* the earth's "line of force"? It is the position which a *freely-suspended* needle would take up if left entirely to itself. In the first place, it would point towards the magnetic pole; and, in the second place, one end would incline downwards at an angle below the horizon corresponding to the "dip" at the place. When, accordingly, the soft iron is held in this direction, it *at once* becomes magnetic by induction—its *lower* end or point acquiring *red* magnetism in our hemisphere, and its *upper* end or handle acquiring *blue* magnetism. This may readily be tested by placing the compass near it. If held a few inches from the lower or red end, the *south* point of the needle will be attracted by the iron; while, if held near the upper or blue end, the *north* point of the needle will be attracted. This invisible force, exerted by the iron, is termed "*induced magnetism*," or "*magnetism of position*," and only remains so long as the iron is held in that particular manner. To destroy it, it is merely necessary to hold the iron in

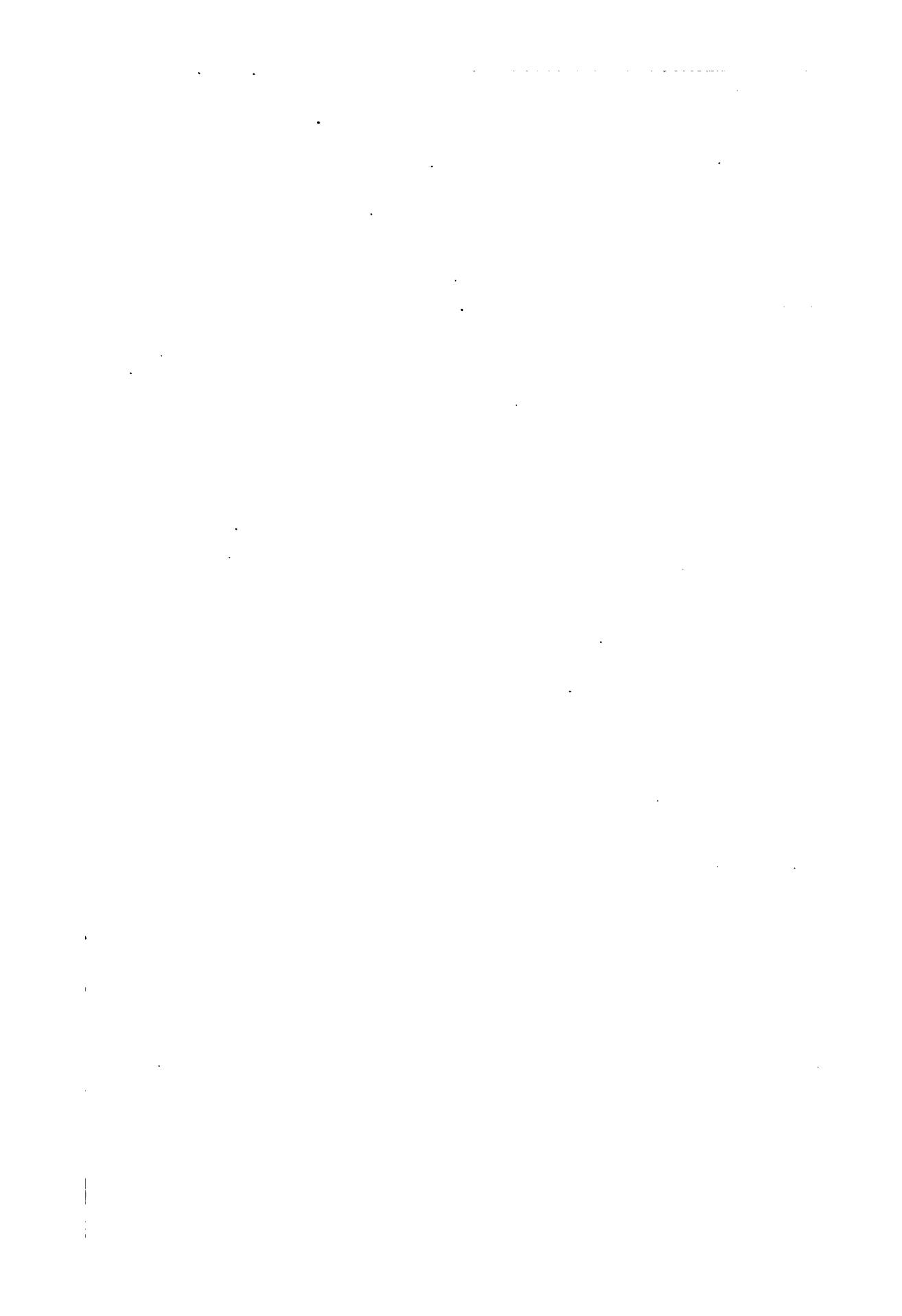


Diagram N° 1.

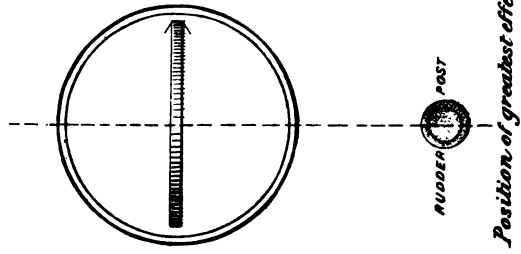
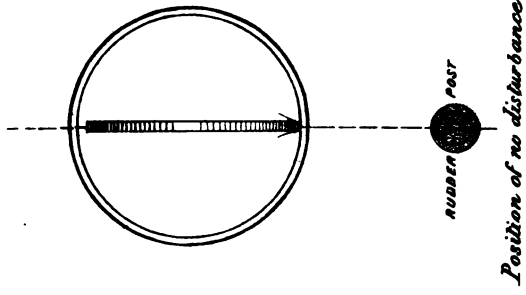


Diagram N° 2



an east and west direction, or at right angles to the "line of force," when it will no longer appreciably affect the compass.

This shows that soft iron has no *fixed* polarity. Percussion exercises a marked influence on both the inducing and dispelling of this kind of magnetism. If, therefore, the iron be hit a few taps with a hammer whilst held in the "line of force," its magnetic power will be intensified; and, again, when the position is altered so as to dissipate the force, it will be found that the tapping hastens that process also.

Let the iron be once more held in the "line of force"—but this time reversed—it will again become magnetic; *but the blue and red magnetism will be found to have changed ends.*

The facility with which soft iron acquires or parts with magnetism may be shown in another way. Take the kitchen poker, in imagination, to the north magnetic pole, and hold it vertically, point down. The lower end, as before, will acquire "red," and the upper end "blue" magnetism. *Holding it still in the same way*, transport it to the magnetic equator; it will there be entirely free from magnetism of any description. *Still holding it in the same manner*, transfer it to the south magnetic pole; it will once more be magnetic, *but* the lower end will now have "*blue*," and the upper end or handle "*red*," magnetism. The rapidity of the change will correspond to the time occupied on the journey.

As before stated, *this will not happen with a magnet of hard steel*, whose poles remain unchanged in character, no matter what way it is held, or in what hemisphere it may be placed.

Thus, in north (magnetic) latitude the upper end of all vertical soft iron, such as funnel, masts, stanchions, davits, rudder, sternpost, &c., has *blue* magnetism, and *attracts* the north end of the compass needle. While as the ship sails south, such iron becomes gradually weaker in its effect, and on the magnetic equator—being then at right angles to the "line of force"—produces none whatever. On the other hand, in south (magnetic) latitude the upper end of this same vertical iron acquires *red* magnetism, and *repels the end of the needle it had previously attracted*, doing so with continually augmented force as high latitudes are gained.

Further, in any given locality the magnetic intensity of a vertical bar of soft iron, such as the rudder post, remains undiminished *no matter what may be the direction of the ship's head*; but its *disturbing* effect on the compass depends upon its position relative to the needle, being greatest when at right angles to the direction of the needle's length, and ceasing when in a line with it (*see Diagrams Nos. 1 and 2*).

A *horizontal* bar of soft iron at the magnetic pole has no magnetism whatever, since there it is at right angles to the "line of force." It is, in fact, in the same harmless condition that the vertical bar found itself on the magnetic equator. When taken, however, into low latitudes, it gradually becomes magnetic *if kept pointing towards the magnetic pole*, and has its greatest power in the vicinity of the equator. The *red* mag-

netism will always be found in the end which points to the north, turn it about as you may.

As the south magnetic pole is approached, a horizontal bar of soft iron loses force, and at the point of 90° dip has again ceased to be magnetic. In brief, vertical iron is most magnetic at the poles, and horizontal iron, held in the direction of the meridian, is most magnetic on the equator.

Another very marked distinction between vertical and horizontal iron must here be noted. The magnetic intensity of the latter depends not only upon its proximity to the equator, *but on the angle it makes with the magnetic meridian*. Thus, when held in a north-and-south direction (magnetic) it is at its best; on being turned in azimuth it loses power, and when held exactly east and west (magnetic), has none at all. Therefore, unlike vertical iron, horizontal iron on board ship has a varying action upon the compass, *depending on the direction of the ship's head as well as the position of its poles relative to the compass needle*.

This is an important distinction; but there is yet another. Horizontal iron produces the same deviation in *all* latitudes; for though its power varies with that of the earth, the ratio between the two is constant; and since the first is the *disturbing* force of the needle, and the other the *directing* force, it follows that the deviation arising from the induced magnetism of horizontal iron is the same at any part of the globe.

A magnet possesses the peculiar power of producing magnetism in a bar of iron or steel without loss to itself, and so is capable of propagating its own species to any extent. Therefore, when trying experiments with a slice, crowbar, or kitchen poker, it must not be placed *too* close to the compass needle, as the latter, if strong, will of itself induce magnetism in the poker when, from the position in which it may be held at the time, none would otherwise exist. Thus, if a common spike nail be held near one pole of a powerful magnet, the latter will first *induce* magnetism in the nail of a *contrary name to itself*, and then the law which says that *opposite poles attract each other* will come into operation, and the nail in obedience will fly to the magnet.

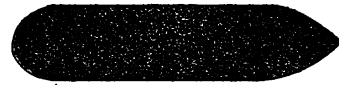
Whatever the process of magnetization may be, it produces two opposite and *equal* forces in the ends of the steel bar, from which it follows that there will be a neutral point about the center of the bar totally devoid of magnetism of any kind. It is well to know this; since, if it be compulsory to put a compass near vertical iron, it may be possible to raise or lower it to the level of the neutral point, and so render the iron incapable of mischief.*

* Magnetism has recently been used for a very curious purpose, as the following account, taken from *Chambers's Journal* for November, 1880, will show: "It is well known that in working iron, such as welding two pieces together, and even in its manufacture, hollow places or flaws occur, with merely an outside skin over the defective parts, which any test but a destructive one would fail to discover. * * * To test

Diagram N°3.

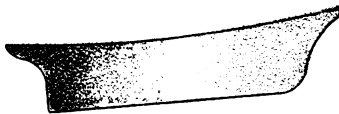


SIDE ELEVATION

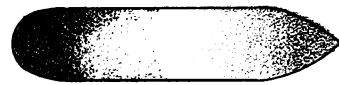


DECK PLAN

Diagram N°4.



SIDE ELEVATION



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Diagram N°5.

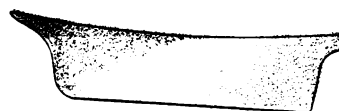


SIDE ELEVATION



DECK PLAN

Diagram N°6.



SIDE ELEVATION



DECK PLAN

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An iron ship may be correctly looked upon as in itself a large permanent magnet. She became so in the process of construction; for, although the materials of which she is built are not such as by themselves retain magnetism permanently, it is found that, when united in the form of a ship, and subjected to percussion by riveting, &c., they acquire this property in a greater or less degree.

After launching and reversal of the ship's head as it was on the building slip, the magnetism undergoes very rapid diminution; but in no case does it depart *entirely*, and that which is left when the saturation point is reached is accordingly styled *subpermanent*. So far, there is a great correspondence between the ship, taken as a whole, and the steel magnet.

It is evident that the position of the poles of the ship's subpermanent magnetism must depend—first, upon the direction of her head when building; and, secondly, upon the “dip” at the part of the world in which she was built. If, for example, a ship were built at the North magnetic pole—direction of her head in this case immaterial—her magnetic constitution would be shown by the subjoined diagram (No. 3).

If built on the magnetic equator (head north), diagram No. 4 would represent the state of affairs.

Diagram No. 5 represents a ship built at the south magnetic pole and in this case also the direction of her head would not signify; and diagram No. 6. shows one built at Liverpool—head south.

Endless diagrams might be drawn to show the effect of the combination of geographical position, with the direction of the ship's head at time of building, on her subpermanent magnetic character, but the foregoing are sufficient to illustrate what is meant.

We have now shown that the compasses of a ship are acted upon, first, by her *general* magnetic character, which, so to speak, was born with her, and secondly, by the *induced* magnetism of individual masses of vertical and horizontal iron.

The general magnetism, after a time, becomes stable in amount, irrespective of geographical position, and the color of its poles are not subject to change; the *induced* magnetism never becomes so, and the color of its poles depends, in the case of vertical iron, upon the mag-

the homogeneity of the metal, Captain Saxby takes a bar of iron and places it in an east-and-west direction. “He next passes a compass with a very sensitive needle along in front of the bar—the needle, of course, pointing at a right angle to it. If the bar is perfectly solid through its whole length, the needle will remain steady. If, however, there should be a flaw or hollow place in the bar, the needle will be deflected as it passes from the solid to the hollow place, *backwards* towards the solid iron; passing on over the hollow place, the needle will come within the range of the solid iron at the other end of the flaw, and will again be deflected *forward*. If the bar be cut through anywhere between these two points of deflection, a flaw will invariably be found. Many thousands of pieces of iron—some prepared for the purpose of testing this method of trial, others in the ordinary course of business—have been operated upon with the same unvarying result.”

netic latitude the ship may be in at the moment; and in the case of horizontal iron, upon the direction of the ship's head.

Although the subpermanent portion of the ship's magnetism remains constant in all latitudes, its *effect* upon the needle is very different. Near the equator, the horizontal or *directive* force of the needle is at its best, and, accordingly, it is then most fit to resist the disturbing pull of the fixed portion of the ship's magnetism just referred to. But, as we know, the needle *loses* its directive force as polar regions are approached, and, consequently, at such times comes more and more under the domination of the ever vigorous subpermanent magnetism. It is consequently necessary to compensate these various effects *by means suitable to each*.

The *permanent* portion of the ship's magnetism, which causes *semicircular or polar deviation*, is compensated by *steel magnets*, whose magnetism is likewise permanent; and that part due to induction in *vertical* iron, which goes and comes with change of latitude, and likewise causes semicircular deviation, is compensated by *vertical* bars of ordinary wrought iron, which similarly become magnetic by terrestrial induction, and are influenced in a corresponding degree by such changes of latitude as both may be exposed to.

Another part of the ship's magnetism, namely, that arising from the induction of *horizontal* iron, produces *quadrantal* deviation—which, as before stated, is the same for all latitudes, and is compensated by *horizontal* cylinders of soft iron. These are usually cast.

The correct principle, therefore, to go upon in adjusting compasses appears to be that "Like cures like," when applied on the opposite side to the disturbing influence.

The many diverse causes shown to operate on the compass at one and the same time, combine in producing a certain sum total of effect, but as these forces do not always act in harmony either as regards direction or amount, it is clear that their joint effect cannot be compensated by any single magnet whose power is the same at all times and in all places. Here the knowledge of the *skilled* compass adjuster comes in, as by certain mathematical rules, he is able to *analyze* the magnetic character of the ship, apportion to *each kind* of deviation its *proper value*, and apply the *right kind* of remedy.

To distinguish quadrantal from semicircular deviation is quite easy, but to separate that part of semicircular deviation caused by *vertical iron* from that part which is produced by the ship's *subpermanent magnetism*, is a more difficult task by far; yet, in vessels continually changing their magnetic latitude, this is of the highest importance.

To adjust a compass, it is necessary to put the ship's head on two adjacent cardinal points, such as north and east; also on any one of the four principal intercardinal points, such as N.E.

The deviation (semicircular) existing when the ship's head is either north or south, is caused by the attraction of the port or starboard side

of the ship, according as the attracting pole of her magnetism lies to one side or the other, and is compensated by steel magnets placed athwartships. The compass being placed in the midship fore-and-aft line of the vessel, and the iron on each side of it being *in general* equally and symmetrically distributed, there is no occasion to compensate the induced magnetism of vertical iron, as that on the port side counteracts that on the starboard side.

In a ship built either due north or south, the poles of her subpermanent magnetism would exist in the bow and stern, rendering thwartship magnets unnecessary, as there would be no deviation on either of these two points; that is, supposing the iron on each side of the compass to be the same in amount and position.* The only effect would be to *increase* the directive force of the needle when the ship's head was on the *opposite* point to that on which she had been built, and to *diminish* it when on the *same* point.

When the ship's head is either due east or west, the deviation (semi-circular) is caused by the attraction of the bow or stern of the vessel, according as the attracting pole of her subpermanent magnetism lies forward or aft, and according to whether the greatest effect of vertical iron is found before or abaft the compass. The compensation in this case is effected partly by steel magnets placed fore and aft, and partly by a vertical pillar of wrought iron.

In a ship built either due east or west, the poles of her subpermanent magnetism would lie to starboard and port, rendering fore and aft steel magnets unnecessary, as there would be no deviation from this cause with the ship's head on either of these points, and the rule as to the directive force of the needle would be the same as before.

It is seldom or never that a ship is built with her head *exactly* on one of the cardinal points, so that both fore-and-aft and athwartship magnets are almost invariably required; and when the compass is so placed as to be free from the effects of vertical iron (which is seldom the case), it is possible, by comparing the natural deviation on the north and south points with that on the east and west, to determine pretty accurately the direction of the ship's head at time of building; or, knowing this latter and the natural deviation on north and south, it is possible to determine how much of the deviation on east and west is due to subpermanent magnetism, and how much to the induced magnetism of vertical iron. This knowledge is very important.†

* When, on the other hand, a compass is flanked by a donkey boiler, or the iron pedestal of an engine-room telegraph on the bridge, compensation on the north and south points would be necessary.

† Rule: Enter the traverse tables, with the correct magnetic direction of the ship's head at time of building, as a course. In the departure column look for the number corresponding to the deviation on north or south, and against it in the latitude column will be found the value of the subpermanent magnetism on east or west, which, subtracted algebraically from the quantity actually observed on one or other of these points, will leave the amount due to vertical iron.

When the ship's head is either N.E., S.E., S.W., or N.W., the remaining deviation (quadrantal) is got rid of by cylinders, or, better still, by hollow globes of cast iron, placed on each side of the compass bowl. The athwartship and fore-and-aft magnets are usually, but not necessarily, placed on the deck *below* the compass. Sometimes it is more convenient to place them on the deck *above*, or on a bulkhead, or inside the binnacle itself. In reality, it matters not whether they are placed above or below the compass, so long as the middle of the magnet's length is in the vertical plane, passing fore-and-aft or athwartships—as the case may be—through the center of the compass card. (See diagram No. 7.)

On no account are *steel* magnets to be applied *end on* to the compass, neither should they be placed vertically, excepting the one used for correcting the heeling error. Therefore, athwartship magnets must be placed either before or abaft the compass, and fore-and-aft ones to starboard or port.

It is preferable to use large magnets at a considerable distance, than small ones close to. The rule is, that the magnet should not be nearer to the center of the card than twice its own length; thus, a 30-inch magnet should not be within 5 feet. But some are so weak that at this distance their effect would be next to nothing. Well-made magnets of equal size will sustain each other's weight.

The cast-iron cylinders or globes, on suitable brackets, are placed on each side of the bowl, so that their centers may be as nearly as possible on the same level as the compass needles, and that a horizontal thwartship line through the center of the card may pass through their centers also. (See diagram No. 8.)

The wrought-iron vertical pillar is generally from 3 to 4½ inches in diameter, and of such a length that when secured in its place the *upper* end may be about 2 inches or so *above* the level of the card. It is more usually placed on the *fore side* of the compass, and exactly in a direct fore-and-aft line with the center of the card; but cases may arise where the balance of effect of the ship's vertical iron lies *itself* on the fore side of the compass, in which case the compensating pillar might have to be placed on the *after* side. The rule is simply this: that the pillar must be placed so that the pole on a level with the compass card may be of such a name as will counteract the pull of the ship's vertical iron; and to accomplish this the pillar may be placed in various positions, being sometimes on the same and sometimes on the opposite side to the force it is intended to compensate. Occasionally it will be found necessary to bolt it to the deck overhead (as in a wheelhouse), so that its *lower* end may hang a couple of inches *below* the level of the card. A good example of this kind of adjustment is shown on diagrams Nos. 12 and 13.

When intending to adjust, choose a fine day with smooth water, provide a number of steel magnets of various sizes,* and mark their cen-

* Magnets for use on board ship are usually soldered in water-tight cases of copper, to protect them from rusting.

Diagram № 7.

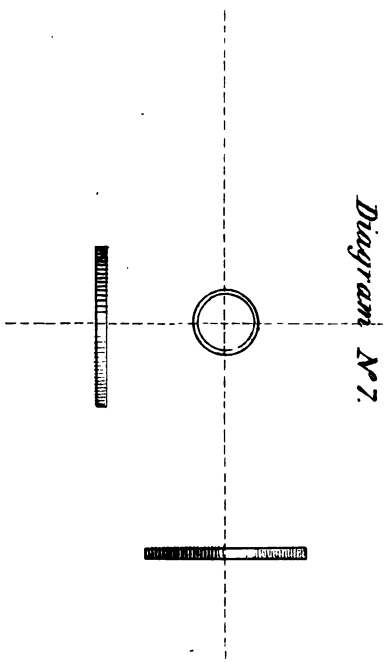
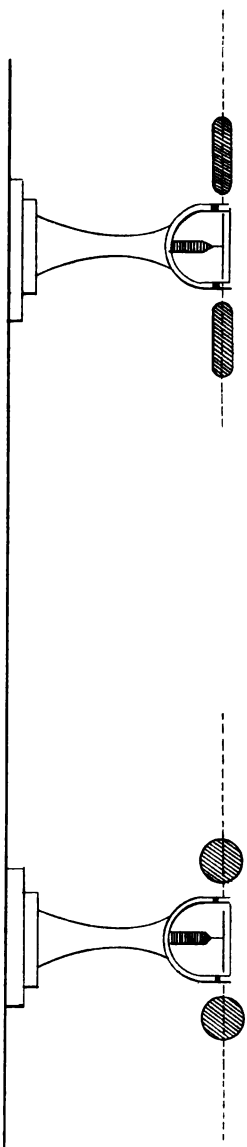


Diagram № 8.



ters. Hold them one by one near a compass, and a couple of inches or so of that end which attracts the north end of the needle paint blue, and the other end red.

Plumb under the center of the compass draw on the deck two chalk lines, one fore-and-aft and the other athwartships, as represented in diagram No. 7. In the case of a wheelhouse compass, do the same *on the under side of the deck overhead*. We will suppose the vessel to be at sea, and that it is intended to use the bearing of the sun. Set the hack watch to *apparent time at ship*. Take out of the azimuth tables the sun's *true* bearing for every four minutes of the time during which you will be occupied adjusting, and convert it into the *magnetic* bearing by applying the variation. Write down in a small pass-book these magnetic bearings and corresponding times.

If a steamer, take in all sail, *trim her perfectly upright* by filling the boats with water or otherwise, slow the engines, provide copper tacks and a hammer, and see that the *lubber-lines of the compasses to be adjusted are truly fore-and-aft*. Place the Pelorus* in one of its stands—near to the man at the wheel, if possible—and appoint an officer who is thoroughly familiar with the instrument to put the ship's head as required, whilst attending yourself to the compasses. Begin with the Standard, being the most important, and leave the steering compass to the last, although there is no reason why its deviation on the various points, as the ship goes round, should not be noted by another officer. All being ready, let the lubber's point of the Pelorus be secured at north, and the sight vanes clamped to the sun's magnetic bearing, then starboard or port the helm until the sun's reflected image is seen in the speculum or mirror fairly bisected by the thread of the vane.

The vessel's head will now be north magnetic. If, now, the compasses were correct, they would agree with the Pelorus in showing the ship's head to be north; if, however, influenced by the iron of the ship, they fail to do so, the amount each differs from it will be the *deviation* due to that particular compass *on that particular course*.

Accordingly, if the north or red end of the compass-card be attracted, say three points to starboard, the ship's head will appear N. W. by N. by compass, or, in other words, the deviation will be three points easterly (+). To counteract this blue *attracting* force of the subpermanent magnetism on the starboard side, place athwartship on the deck—either before or abaft, above or below the compass, as most convenient—a steel magnet *with its red end to starboard*, and, consequently, *its blue end to port of the compass*. The red end of the magnet will of course repel the red end of the needle *from* the starboard side, and be aided in doing so by the equally strong attractive force *to* port of the blue end of the magnet.

* This is a dumb compass, or alidade very similar to the new *standard alidade* recently devised at the Bureau of Navigation. The *standard alidade* is not mounted on gimbals, while the Pelorus is; this constitutes the principal difference.—T. A. L.

To avoid setting up a swinging motion, let the magnet at first be placed a considerable distance from the compass—say four or five feet—and put its center mark exactly on the fore-and-aft chalk line. Then move it gradually closer, until the ship's head is north by the card.

The pull of the starboard side will now have been neutralized by the combined action of the poles of the magnet, which may be lightly tacked down in its place. This is shown in diagram No. 9. Adjust each of the other compasses in a similar manner, placing the red or *repelling* end of the correcting magnet to starboard or port, according as the north end of the compass needle is *attracted* to starboard or port by the ship. If one magnet be insufficient to correct the deviation, apply another, putting it, if possible, on the opposite side of the compass to the first; or, if the first be on the deck *under* the compass, the second may, if desired, be tacked to the deck *above* it. *But in every case similar colors must point in the same direction, or they would neutralize each other.* All this time the officer at the Pelorus—duly provided with watch and pass-book—is altering the setting of the sight vanes for every half degree of alteration in sun's bearing, and is conning the ship *with small helm*, so as to keep her steady on the north point magnetic, signaling by whistle whenever she is exactly so.

Having taken a second look at each of the compasses, and made any alteration which may be required, screw the lubber line of the Pelorus to east; and, keeping the vanes set to the sun's magnetic bearing, bring the ship's head around with port helm until the sun's image is once more seen in the speculum, and *steady her* carefully on this fresh course. The various compasses, if correct on this point, ought *also* to show the ship's head as east. Should they fail to do so, the difference is the deviation, which must be corrected *partly* by fore-and-aft magnets of steel, and *partly* by the upright iron pillar.

The means taken to determine *how much* is to be corrected by one, and how much by the other, will be shown further on; in the mean time, imagine half the deviation to be corrected by the pillar, and half by the steel magnet. If, now, with the ship's head at east magnetic the needle be drawn two points towards the stern,* the ship's head by compass will be E. S. E. To counteract this, place a steel magnet fore-and-aft ways, either to starboard or port of the compass, with its red end *also* towards the stern, and center mark on the thwartship chalk line. Move it slowly towards the compass till half of the westerly deviation is corrected. The ship's head will now be E. by S. by compass. Next place the upright pillar *forward* of the binnacle at such a distance as will cause the ship's head to appear due east, when it may be securely bolted down to the deck. It is preferable, however, that the lower end of the pillar should be let down some distance *through* the deck, and rest either on the one below or on some firm support provided for the purpose.

* When speaking of the needle being attracted or repelled, its *north* end is always meant, unless otherwise specified.

Diagram N° 9.

SHIP'S HEAD NORTH, MAGNETIC.

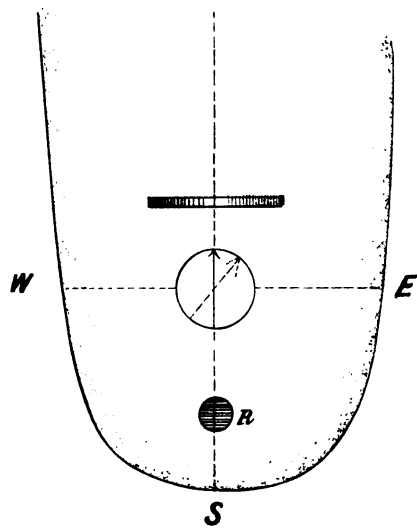
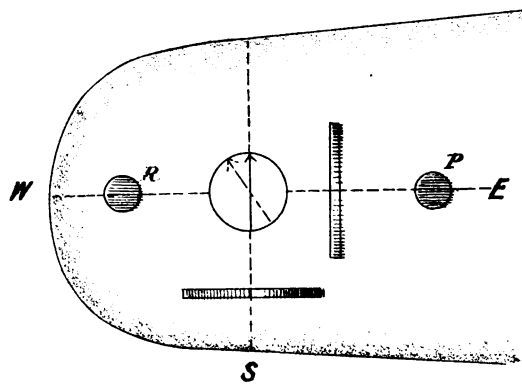


Diagram N° 10.

SHIP'S HEAD EAST. MAGNETIC.



The object is not only to intensify its power, but to keep the *lower* pole of the pillar from being so near as to counteract the opposite effect of the *upper* one. The compass at this stage is shown in diagram No. 10. R. stands for the rudder post, which in this case is the active vertical iron, and P. for the pillar which is intended to counteract it.

The *semicircular* deviation of all the compasses is now corrected. We have still, however, to deal with the *quadrantal*.

Put the ship's head *by Pelorus* on any one of the four principal intercardinal points—say N. E. magnetic. In 99 ships out of 100 the compasses will exhibit *easterly* deviation on this point, amounting to as much sometimes as 10° or 12° . Should this be the case, a cast-iron cylinder or globe must be placed on each side of the compass-bowl, and moved nearer to or farther from it till the ship's head points correctly to N. E. *by compass*. The ends of the correctors must not, however, be nearer to the center of the card than $1\frac{1}{2}$ times the length of the longest needle. They effect their purpose by becoming magnetic by terrestrial induction. For example, with ship's head N. E., their *port* ends exhibit *red* magnetism, and in this position compensate *easterly* deviation, but on turning the ship round to N. W. their *starboard* ends acquire red magnetism, and in this fresh position compensate *westerly* deviation. Chain boxes, though in very common use for this purpose, are not to be recommended. The best corrector of quadrantal deviation is a couple of hollow cast-iron globes or shells.

Here may be mentioned incidentally a curious and oftentimes important fact with respect to all hollow iron bodies, whether globular or square, such as water-tanks, &c., namely, that as soon as the thickness of the sides has reached to one-tenth of the thickness or diameter of the whole body, the magnetic effect is the same as if the body were a solid piece of iron.

The compass is now shown fully adjusted in diagram No. 11.

Semicircular deviation is so termed because it has the *contrary* name in *opposite semicircles*; thus, if it is easterly on north, it will be westerly on south. On the other hand, *quadrantal* deviation is so termed because it has the *same* name in *opposite quadrants*, and the *contrary* name in *adjacent* ones; thus, if it is easterly on N. E., it will be easterly on S. W. also, but westerly on S. E. and N. W.

Steel *fore-and-aft* magnets produce their greatest effect on east and west, diminishing to nothing on north and south, when they become parallel to the compass needle. A vertical iron pillar placed on the center line before or abaft the compass acts in the same way. Steel *thwartship* magnets produce their greatest effect on north and south, diminishing to nothing on east and west, when they become parallel to the compass needle.

Quadrantal correctors produce their greatest effect on N. E., S. E., S. W., and N. W., tapering off to nothing at north and south, east and west. When the ship's head is on north or south magnetic, the poles

of cast-iron cylinders, being at right angles to the "line of force," are powerless to affect the compass; and when the ship's head is on east or west magnetic, though the cylinders are then magnetic they cannot affect the compass, as their poles are parallel to the needle. In the case of cast-iron globes, their magnetic poles are parallel to the needle on all four of the last-named points, but the effect is the same as with the cylinders.

When the process described above is accurately carried out, and the compasses well made and properly situated, they will be *nearly* correct on *every* point. Nevertheless, it is prudent to steam the ship completely round, steadying her on every fourth point by Pelorus, to determine remaining errors.

Then, should any compass be found to have considerable deviation—say 4° or 5° —on the *opposite* points to those on which it has been adjusted, *halve the error between the two*. If, for example, you find a compass correct on north, but 4° out on south, move the thwartship magnet so as to reduce the error on south to 2° , which will, of course, cause 2° of error on the north point also. When necessary, do the same on the W. and S. W. points likewise. After which, swing ship for a table of remaining deviations on every *second* point. When this inequality occurs, it shows that the ship's iron is not symmetrically distributed round about the compass in question.

Having finished, nail the magnets down for good, and cover them with neat cases of hard wood.

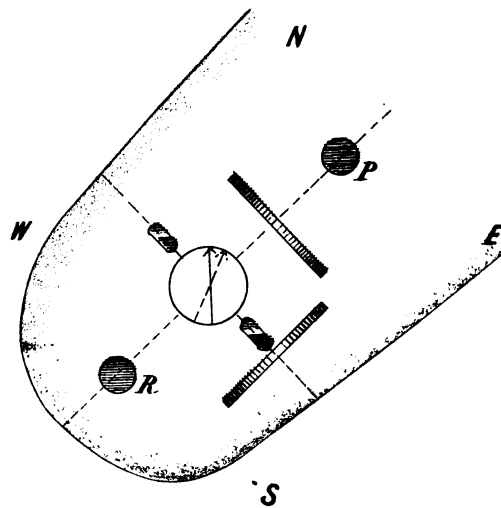
Few people are alive to the fact that in high latitudes a *wooden* tug-boat may be a source of trouble to the compass, if, when fast alongside, the upper end of the funnel is about the level of the bridge or standard compasses, and not many feet from them. An instance of this occurred not a month since, in Queenstown harbor, when the standard compass of a ship was affected to the extent of 3° by the funnels of the passenger tender. Thus an apparently trivial cause might lead to serious results.

It is now necessary to go back a little, and explain the manner of getting at the *correct* amount of deviation to be compensated by the vertical pillar of soft iron. When the ship's head is either east or west, any deviation then existing arises partly from subpermanent magnetism resident in the bow and stern (which must be compensated by a permanent steel magnet), and partly from the induced magnetism of vertical iron predominating more at one end of the ship than the other. This latter must be compensated by a like cause applied in the opposite direction. Thus, if vertical iron, situated *abaft* the compass, pulls the needle towards it, another piece of vertical iron can be put *forward* of the compass to pull it back again; or it may even be placed *abaft* the compass, on the same side as the disturbing force, if the deck fittings will permit of its *repelling* pole being placed on a level with the card.

It has been shown that on the Magnetic Equator vertical iron ceases

Diagram N° II.

SHIP'S HEAD N E. MAGNETIC.



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to be magnetic, and is consequently powerless to affect the compass. *If, then, the deviation be ascertained on the cardinal points when the ship is on the Magnetic Equator, it is certain that it cannot be due to vertical iron.* It must be owing either to *subpermanent* magnetism, or to *retentive* magnetism, to be explained hereafter. For the present let us assume that it is subpermanent only, and correct it by a steel magnet; which being done, let the vessel proceed to high latitudes, and let the deviation be again determined. Then, that arising from subpermanent magnetism having already been cured on the equator, and being, moreover, *when compensated*, not sensibly affected by change of geographical position, we know that whatever now exists is principally due to vertical iron, and should therefore be corrected by a vertical iron pillar, applied as already explained. In practice, the experiment on the equator is only tried on the east and west points, as vertical iron, from its symmetrical arrangement in the ship, seldom disturbs the compass on the north and south points.

Again, supposing a vessel to have been built with her head due north: this will have constituted her a subpermanent magnet, whose axis lies exactly fore-and-aft, the bow being the red, and the stern the blue pole. When such a ship is placed head east, the red bow repels the needle, causing westerly deviation; and unless she proceeds to the Magnetic Equator, there is no way of telling how much of it arises from the cause just mentioned, and how much from the induced magnetism of vertical iron.

On the other hand, suppose the ship's head to have been due east when building, then the entire port side would be subpermanently red, and the starboard side blue. Now, what deviation would this cause when the ship's head was east or west at any after time? None whatever. Since the poles of the ship's subpermanent magnetism and the needle itself would lie in the same straight line, *the only effect would be to diminish or increase the directive force of the needle.* Nevertheless, on trial, there is found to be large deviation on these points. If so, it must be due to masses of vertical iron situated either before or abaft the compass, according to the direction of the pull, and is capable of easy cure by one or more upright pillars applied in the proper manner.

There is another point in connection with the *diminished* directive force of the needle which should not be overlooked; namely, that when the ship is steering in the same direction as that in which she was built, the compass *when uncompensated* will be both sluggish and fickle. Therefore, every master of an iron ship should endeavor to learn in what direction his ship was built, and, when sailing on that course, be more than ever on his guard against the seemingly mysterious pranks of his compass.

The forward wheelhouse compass of the steamship "———," commanded by the writer, from its extremely bad situation, affords a good example of difficult compass correction. Previous to adjustment, this

compass—although an excellent 12-inch liquid one, by Cairns, of Liverpool—had enormous natural deviations. Diagrams 12 and 13, drawn to a scale of 0.3 inch to the foot, show the steps taken to correct it.

From the very close proximity of the mainmast, which acted as a powerful magnet, it was evident from the outset that strong measures would have to be taken with this compass. Experiment showed that, at this level, which was below the "neutral point" of the mainmast, the latter had north or red polarity, and exerted a strong repellent action on the needle.

In due course the ship was swung, and her *natural deviations* carefully ascertained all round. Having been built with head N. 68° E. magnetic, the deviation on north should have been twice and a half as much as that on the east, *were the compass undisturbed by vertical iron*. Knowing what it actually was on both these points, it became a comparatively easy matter to roughly separate the inductive from the sub-permanent. Accordingly, two round bars of wrought iron, each 4 inches in diameter, were used to counteract the mainmast. The after one—48 inches in length—was let down through the top of the wheelhouse, and the other—42 inches in length—was bolted to the deck just abaft the mast.

It will be noticed, on looking at Diagram No. 13, which represents the ship's head in an easterly direction, that the north end of the needle was forcibly *repelled* by the mast. Now the *upper end* of the vertical pillar between the compass and the mast strove to *pull* it back again, and in this it was aided by the *lower end* of the pillar abaft the steam steering-wheel, which *repelled* or pushed it back in the same direction. The distance of these pillars from the compass was so arranged that when in position they about compensated the deviation due to the inductive magnetism of vertical iron; the remaining deviation on the east and west points was corrected by two 16-inch steel magnets, tacked on fore-and-aft ways to the *under side* of the deck *above* the compass. The deviation on the north and south was compensated by one 30-inch thwartship magnet tacked on to the outside of the forward bulkhead; and the *quadrantal* deviation (10°) by two cast-iron cylinders with globular ends, something like the old-fashioned clock weights, each being 12 inches long by 3½ inches in diameter.

This formidable array of magnets reduced the huge errors of the compass within more manageable bounds, but afterwards, when at sea and the ship listed over, the heeling error was excessive, and had to be compensated in the usual way, by a *vertical steel magnet* placed exactly under the center of the card when the vessel was upright. Two iron ventilators, marked V, were also removed. *Nevertheless, this compass was extremely wild and fickle during the first and second voyages, and although it afterwards behaved somewhat better when the ship's magnetism had settled down, it could not be said to give very satisfactory results at any time. Of course, the builders should never have placed the wheelhouse in such a ridicu-*

Diagram N°12 **SIDE ELEVATION.**

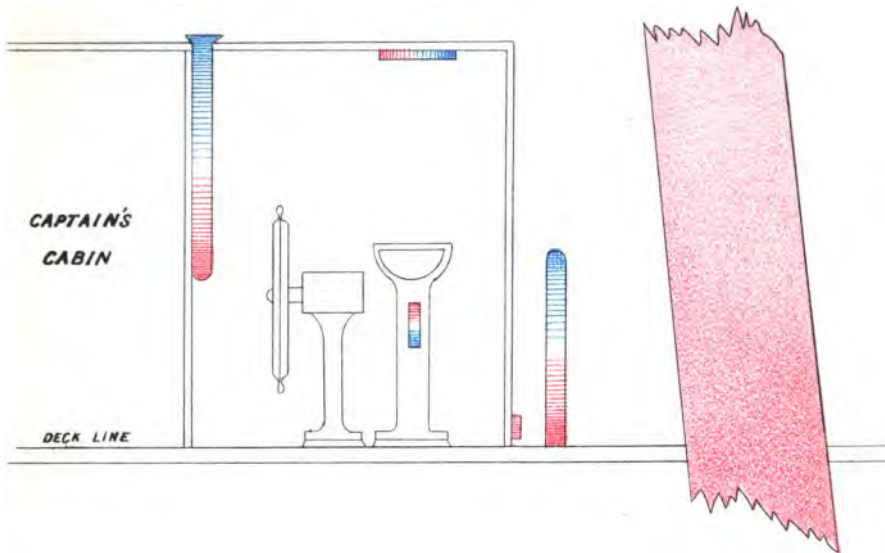
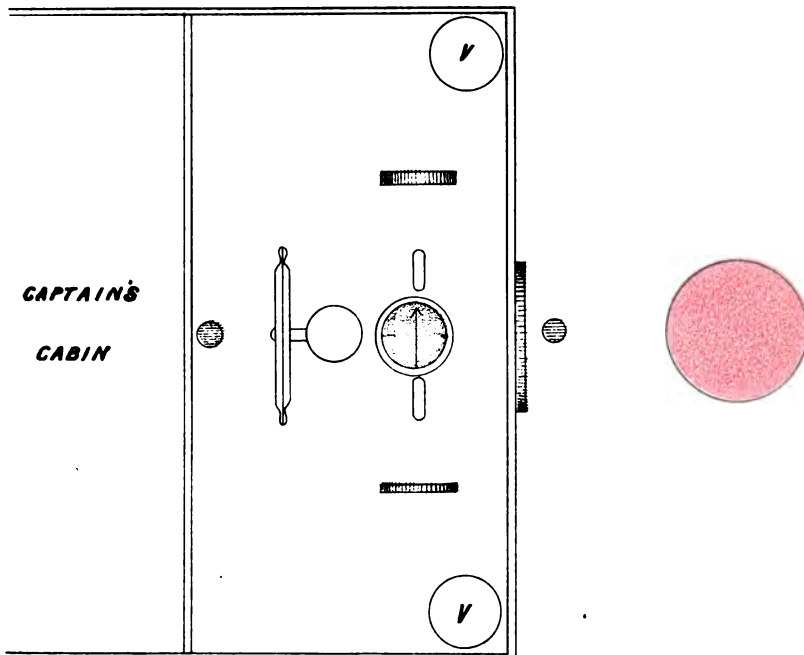


Diagram N°13. **GROUND PLAN.**



lously unsuitable place; but being there, and no way of improving matters short of putting in a wooden mainmast, it was necessary that the captain should know how to make the best of a bad job.

The reader will perceive, from the very unusual character of the conditions named, that in the case just quoted the amount of deviation to be compensated by the wrought-iron pillars could only be approximately inferred; and it is probable that, if ever this ship gets down to the Magnetic Equator, some little alteration of these arrangements will be found advisable.

To avoid confusion of ideas, it has been considered wise to leave for separate consideration that part of the ship's magnetism which is known by the term "retentive." It plays, however, a very important part in the deviation of compasses, and will be found to modify to some extent what has been said in the previous pages.

It has been stated that when a soft iron rod is held in the "line of force," it *instantly* becomes magnetic; or, more correctly, that the latent or dormant magnetism within it has undergone excitation when held in that particular manner. This statement is correct so far as it goes, but it is necessary to supplement it by saying that the longer the rod is so held the more magnetic it becomes—up to a certain point. Again, when the rod is held at right angles to the "line of force," it loses its magnetism; but if it has previously stood *for a long time* in the "line of force," it will not lose it instantly, but will require a long or short period to get rid of the magnetic charge, according to its intensity and the quality of the iron in which it was excited.

Now, this is just what happens when a ship's head has been in one direction for a long time. She becomes temporarily magnetized by the earth's inductive force, and this action is intensified by the sea striking her, and also, in the case of a steamer, by the tremor imparted to the hull by the engines. The poles of the magnetism are of course parallel to the Magnetic Meridian. Thus, if the ship sailed due south for a week or so, her stern would acquire red and her bow blue magnetism, the new charge being superimposed on what may be called the ship's *natural* magnetism, and, to a certain extent, masking it.

"Retentive" magnetism remains for a considerable time after the cause is removed—frequently for days—unless the direction of the ship's head be exactly reversed, when it goes more quickly, giving way to the opposing influence of the magnetism proper to the new direction of the ship's head.

This is a *most important phase* in the magnetic character of a ship, and any one who chooses to investigate it, will see *that for this reason alone* an adjuster's *deviation table* is comparatively worthless. Thus, if a ship had been lying in a dock, say head south, for several months, or even weeks, and was then most carefully adjusted, and replaced in her original berth to load for sea, but with her head in the reversed direction, it would be found before sailing that her compasses had comparatively

large deviations, though when the adjuster left the vessel a fortnight previously they were practically free from error. Every one intrusted with the navigation of an iron ship should keep this fact continually before him. The immediate effect of *retentive magnetism* upon the compass of a ship at sea is to cause her, on a change of course, to *deviate invariably in the direction of the last one*. If a vessel has been steering—let us say south—for some time, and is then hauled up west, it will be found that the deviation on that point will be increased if westerly, and diminished if easterly, *the change frequently amounting to a point and upwards*; so that, unless allowed for, she will infallibly be thrown to the southward of her intended course. Even in shaping a fresh course, differing only a couple of points from the last one, this propensity of the compass must be taken in account according to circumstances, as it varies much in different ships, and in different compasses on board the same ship.

As an illustration, we will take the case of the lines of steamers running constantly between Liverpool and New York or Philadelphia. On the westward passage these vessels have their heads in a westerly direction for upwards of a week, and consequently the poles of their *retentive magnetism* lie to starboard and port—the red pole on the starboard, and blue pole on the port side. The tendency on subsequent northerly courses will be to throw the ship to the westward. Thus, entering New York Bay by the south channel, the Swash range-lights come in one bearing N. 40° W. magnetic; but if, when in one, the vessel be steered directly for them, the direction of her head *by compass* will probably be about N. 33° W., or even more to the northward. The same effect will be still better shown when hauled up for Fort Hamilton. The course keeping the range-lights in one astern is N. 13½° E. magnetic, but the chances are in favor of the vessel having to steer about N. 23° E. *by compass*, or, at all events, considerably to the eastward of the proper course.

The same thing occurs in the Delaware. From Cape Henlopen to the Brandywine light-house, the course—keeping the ranges in one astern—is N. 2¾° W. magnetic; it is quite common, however, to steer about N. 12° E. by compass.*

On the eastward passage, these steamers, having had their heads to the eastward for a week, get magnetized in the opposite direction. It is the *port* side which now has *red* magnetism; and, in consequence, when hauled up at Tuskar for the Skerries or South Stack, instead of steering N. 58° E. magnetic, they have generally to shape a *compass course* many degrees to the northward.

As the effects due to crossing the Atlantic are about equal going and coming, it is not a difficult matter to adjust the compasses with accuracy

* In trans-Atlantic steamers it is a good plan to have one of the deck compasses adjusted for the American port frequented, and another for the English port. The writer keeps his bridge compass adjusted for the Delaware, and the standard or navigating compass for the Irish Channel.

for the ship's subpermanent magnetism on the north and south points. If, for example, westward bound, with head north by compass in the Delaware, the deviation is found to be 8° *westerly*; and eastward bound, with head north outside Queenstown, it is found to be 20° *easterly*; the amount of *subpermanent* magnetic attraction to be compensated by the thwartship magnets is 6° easterly. Accordingly, at one or other of these places the magnets should be moved to correct 14° of deviation—due to retentive magnetism only, which amount of 14° will be westerly deviation in the Delaware, and easterly at Queenstown. It is evident that were it due to *subpermanent magnetism*, it could not, on the same point, be easterly at one time and westerly at another. But, in making these observations and corrections, *do not forget that the ship must be perfectly upright, or the results will be vitiated*. From half-passage over either way, it will be easy to adjust on the east and west points; as by that time the retentive magnetism on north or south will have disappeared.

No possible amount of care or scientific knowledge in an adjuster can provide against *retentive magnetism*. There is, however, one means by which its effects can, in some measure, be modified. In those regular liners always sailing on the route just specified, it will probably be found useful to *over-compensate the quadrantal deviation*. The correctors diminish westerly deviation in the N. W. quadrant, and easterly deviation in the N. E. quadrant; therefore, by *over-compensation* the effect of the retentive magnetism would be partially neutralized in one semicircle of the compass at both ends of the voyage; and so long as the course lay within that semicircle, there would be undoubted advantage. On the other hand, those liners which run principally in a north and south direction, and have occasion to make abrupt changes of course near the end of the passage, should have their quadrantal deviation *under-compensated*, or, if small, neglected altogether.

These last are not so fortunately situated as the first named, since the application of correctors for quadrantal deviation has not only the effect of increasing the directive force of the needle, but lessens very considerably the error due to heeling.* Each one, therefore, must judge for himself how far these suggestions are suitable to his own particular route and ship. Pole compasses, *when well placed*, are comparatively exempt from the effects of retentive magnetism, and masthead compasses are almost entirely so.

Now, this matter of *retentive magnetism* has a very important bearing upon compass adjustment. It is evident that if its effects get mixed up with the ship's *natural* magnetism, the adjuster will be compensating something which would ultimately have disappeared of itself, or perhaps have taken an opposite name. This is another reason why a

* The quadrantal deviation in all these cases is supposed to be of the kind due to the coefficient $+D$; that is, easterly in the N. E. and S. W. quadrants, and the contrary in the other two.

deviation table cannot be trusted, and by imparting undue confidence is more likely to lead into trouble than to keep one out of it. It shows also that, before the captain of a ship undertakes to meddle with his compasses, he should be tolerably certain that they are free from this fleeting but troublesome error, or else know by experience how much to allow for it.

The numerous lines of steamers running to Eastern ports through the Suez Canal have a splendid opportunity for adjusting their compasses in the most perfect manner. In the first place, between Aden and Ceylon—a distance of over 2,000 miles—they are steaming nearly due east on the magnetic equator, during which time, of course, vertical iron has no effect whatever on the compass. Therefore, when about half-passage over, let the ship's *subpermanent magnetism* be carefully compensated with fore-and-aft magnets of steel on east magnetic.

As, however, the deviation existing on the east course may be due partly to the ship's *natural magnetism*, and partly to the *retentive magnetism* picked up coming down the Canal, Gulf of Suez, and Red Sea, it will be proper, at the same place, on the return passage, to ascertain the deviation on the west point. Should there be any, it ought to be reduced one-half, by shifting one of the fore-and-aft magnets in the required direction, and when the ship gets up by Beachy Head or Dover, *again* determine the deviation on the east point.

It may now be pretty large, and if not mixed up with *retentive magnetism*, will be due wholly and solely to the influence of vertical iron. Now is the time to place the upright iron pillar, and let it be at such a distance as will compensate all the deviation on east, unless there is reason to believe that some of it arises from that troublesome *retentive magnetism*, in which case allow, say, a couple of degrees to remain. It is not, however, likely that there will be much "retentive" left by the time Beachy Head is reached; but if the weather is fine, you can make tolerably sure by heading the vessel right off to south for 20 minutes or half an hour, going slow, and then putting her on east, magnetic, to be adjusted.

Should the iron pillar be made to bolt to the deck on which the binnacle rests, it will be merely necessary to move it nearer to or further from the compass, till the ship's head points to east, magnetic, by compass as well as by Pelorus. But if, as recommended, the pillar has been made to let down through the deck, you must ascertain *beforehand* the effect, at various distances, produced by it on this particular compass, taking care that the experiment is made in the same magnetic latitude as that in which it is intended to ship the pillars.

When the writer was in the steamship City of Mecca, this plan was adopted with complete success. The deviation on east was ascertained off Dover, and noted. On arrival in London, a round wrought-iron pillar, 5 feet long, and $4\frac{1}{4}$ inches in diameter, was procured, and its inductive power tested, as follows: The compass (12-inch card, 4 needles) was

taken on shore in the S. W. India Dock, and placed on some cotton bales, at such a height that the pillar stood a couple of inches above the level of the needles. As soon as the card had ceased vibrating, a piece of marline was stretched across the center of the compass in an east and west direction, and made fast. The iron pillar, which had purposely been left standing on end for some hours, was next, with the assistance of an impromptu plumb-line, placed vertically under the marline, in which position it was of course at right angles to the direction of the needles, and consequently exerting its greatest influence. Having measured the distance of the pillar from the compass—center to center—and noted the effect produced, it was advanced—*still under the marline*—a little nearer, the measurement repeated, the effect again noted, and so on.

The following shows the results, and may be useful to others under similar circumstances, but only as a rough guide, since different qualities of iron, and a different construction of compass, may increase or diminish the values here given:

Distance.		Effect.
ft.	in.	°
7	6	None.
6	7½	1½
4	7½	3
3	6½	6½
2	9½	11½
1	11½	25

Having by this method determined the distance at which the pillar would compensate the amount of deviation ascertained off Dover, a hole was bored in the deck at the same distance from the compass, and the pillar let down until its upper end stood about two inches above the level of the card, and the heel rested on a strong wooden cleat or bracket, screwed to a bulkhead below. The partners were then wedged up with soft wood, and a duck coat put on over all, and painted, to preserve the pillar from rust.

To adjust compasses on the north and south points, there is a capital place for these eastern-going ships in the Suez Canal. Just after leaving Port Said there is one unbroken magnetic course (S. 4° W.) of 26 miles; and as the speed in the Canal rarely exceeds 7 knots, there will be 3½ hours available for adjusting. It is true the vessel's head cannot be put *exactly* on south magnetic; but if the thwartship magnets are placed to make the compass show S. 4° W., when the vessel is pointing straight down the Canal, this will be found quite near enough.

The next matter is how to get rid of the *retentive* magnetism acquired whilst steaming on an easterly course in the Mediterranean, which will naturally produce its greatest temporary effect now that the vessel's head is south, or at right angles to its former direction.

It is usual to coal at Port Said; or if a steamer arrives late in the afternoon, it is seldom that she can proceed before the next morning.

If, during this unavoidable detention, the pilot can be prevailed upon to put the vessel into the Ismail Basin, she will there head to the north-west; or in the opposite direction, to the courses steered down from Malta; and will be almost sure to have lost all her *retentive* magnetism before the following morning.

Even should it be found impossible to get the ship's head in this direction, the ordinary berth for waiting steamers runs about SW., or some ten points from her last course, which will go a long way to remove the unwelcome visitor. If in any doubt, however, the compasses can again be tried on south, when emerging from the Canal into Suez Bay, by which time they will certainly be free from the effects of the "Retentive" acquired on easterly courses.*

The compass has now been corrected on the cardinal points, but there is yet the *quadrantal deviation* to deal with. Fortunately *in this case* the presence of any amount of *retentive magnetism* does not signify in the slightest degree. At any convenient time or place, steam the ship right round the circle, steadying her sufficiently long on N. E., S. E., S. W., and N. W. *by compass*, to get the deviation on these points with accuracy. Mark easterly deviation by the plus (+) sign, and westerly by the minus (−) sign, and then proceed as follows: *Reverse* the sign of the deviation observed on S. E. and N. W., then add together those which have the same sign; take the difference between the two dissimilar quantities thus found, and prefix the sign of the greater. Divide this difference by 4, *retaining its sign*, and the result will be the *quadrantal deviation*, which in its natural state, without correctors, will nearly always be + in name; and as it is due to horizontal iron, will retain the same value in any latitude, unless indeed the construction of the vessel be materially altered, or large quantities of iron be shipped as cargo. The following example is taken from the record of the *British Crown's* compasses.

BELFAST LOUGH. Monday, 6, 10, '79.

The natural deviation on N. E. was − 6°, on S. E. − 62°, on S. W. + 32°, and on N. W. + 48°.

N. E. − 6°	S. E. + 62° sign reversed.	+ 94°
N. W. − 48 sign reversed.	S. W. + 32	− 54
—	—	—
− 54°	+ 94°	4) + 40
		—
		+ 10° = Quadrantal deviation.

To compensate it; if the sign is + as in the example, put the ship's head the same number of degrees *to the left* of N. E. as the value of the

* In the so-called *steel* ships now coming into fashion, the writer finds, as might be expected, that their magnetism is of a more fixed character as compared with iron ones. The deviations of the compasses in steel vessels are therefore somewhat more constant, which in itself is a great advantage, since in general it is not so much the *amount* of deviation that is complained of as its perplexing variability.

quadrantal deviation; and, keeping her exactly in this direction by the aid of some other compass, place the correctors, and move them closer to, until her head is N. E. by the compass under treatment. Ships are so seldom found having quadrantal deviation with a — sign, that it is unnecessary to enter upon its compensation.

Although the quadrantal error is rarely large in amount, like the semicircular, it is for many reasons very important that it should be corrected. Not the least is the fact, that for the same amount of maximum error, the quadrantal changes *twice* as rapidly as does the semicircular error; and, therefore, a quadrantal error of 10° is much more embarrassing than a semicircular error of the same amount. The true significance of this will be seen when it is explained that a quadrantal error of 10° implies a rapid change in the deviation of the compass, amounting to as much as half a point, with so small a change as a point and a half in the ship's course from one side to the other of any of the four cardinal courses. Imagine the difficulty of trying to steer by such a compass:

This concludes the adjustment of a ship upright in which only the pull of the *horizontal* portion of the ship's magnetism has duly been considered. Some iron vessels, however, have excessively large deviations, due to magnetic force *below* the compass, since the poles of the ship's magnetism can only lie in the horizontal plane in such ships as have been built on or near the magnetic equator. This heeling error has been known to amount to as much as 2° for every 1° of heel. It is greatest when the ship's head is on the north or south points, and becomes reduced to a very small quantity on east or west. Thus a ship changing her heel from 10° port to 10° starboard, may change her deviation as much as 40° .

It is seldom or never possible to list a ship in dock to ascertain her peculiarity in this respect, as doing so costs too much time and money in these days of rapid movements and economy; but it may be approximately arrived at in another and much easier way. Get an optician of *repute* to make you a delicately poised dipping needle, mounted on a suitable stand, carrying a couple of spirit levels, and protected with a glass cover. Let the needle point traverse a vertical scale of degrees, and be fitted with a small sliding balance weight, so that whatever part of the world you may be in, by moving the weight you can set the needle to zero of the scale, when the spirit levels indicate that the instrument is perfectly horizontal. Now, to test the vertical force of the ship on any compass, take your dipping needle on shore, *in a spot free from local attraction*, and adjust it to zero; then, returning on board, remove the compass, and put the dipping needle in its place, bedding it up with wood or otherwise until it is perfectly leveled, and occupies *exactly* the same position and direction the compass needles did. Then, if it be found deflected from zero, it shows the existence of vertical magnetic force *below* the compass, commensurate with the amount of such

deflection. This can be compensated by inserting a vertical steel magnet in a suitable receptacle, directly underneath the very center of the instrument; which magnet is to be slid up or down till the point of the dipping needle again rests at 0° , when it is to be secured in place, and the compass returned. Generally it is the red pole of the magnet which requires to be uppermost, but this is very easily seen on trial.

This is a very important adjustment in all ships, but more especially in those whose cargo is largely composed of iron; and as it is certain that such vessels cannot be heeled every voyage, such a simple and inexpensive mode of effecting it should not be neglected. Unfortunately, this adjustment, as at present effected, only holds good for the magnetic latitude in which it is made.

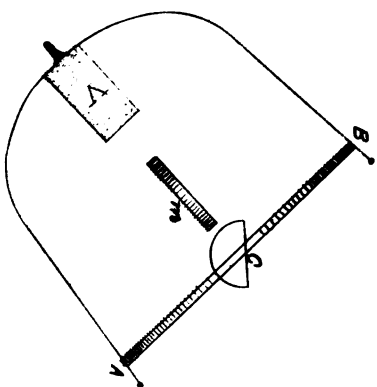
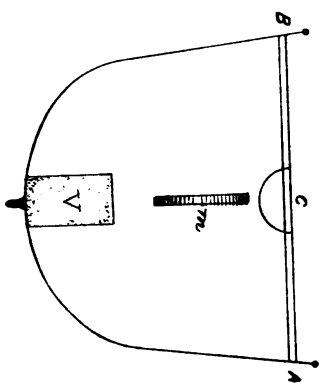
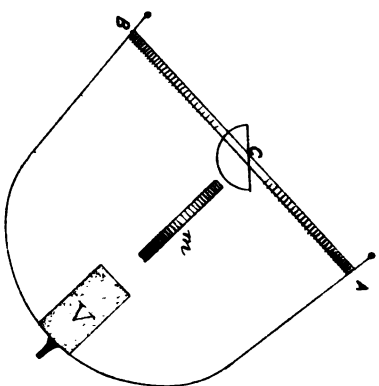
The vertical force below the compass is compounded of induced as well as subpermanent magnetism; and we have shown that these require different treatment, inasmuch as the *transient* induced magnetism of soft iron cannot be satisfactorily compensated by *permanent* steel magnets. Moreover, iron which was horizontal with the ship upright partakes also of the nature of vertical iron when she heels over, which at once introduces a fresh disturbing element. This adjustment, therefore, can only be considered reliable in such *foreign-going* vessels as the Atlantic liners before alluded to—which, in the run from the United Kingdom to New York, are all the time practically in the same magnetic latitude, the difference not amounting to 3° .

To see what a great advantage a vessel has whose heeling error is compensated over another where it is not so, just suppose them to be on northerly or southerly courses in a rough beam sea. In the one case, each time the ship rolls, the vertical magnetic force below the compass will come out now on one side and now on another, causing the card to be alternately pulled to starboard and port at every roll; and should this pull happen to coincide with the period of vibration due to the motion of the ship, the swing of the card will be so great as to render it perfectly useless. In such cases, a man ignorant of the science of compass adjustment will be almost certain to attribute the excessive swing to some inherent fault of the compass. On the other hand, the properly compensated compass will remain comparatively steady under all circumstances, and any little swing will be due to purely mechanical causes.

In the subjoined diagram, let V in each of the figures represent the vertical component of the ship's magnetism, and its effect on the compass-needle, when the vessel rolls, will be easily understood. B represents the deck beams, C the compass, and M the compensating magnet. (See diagram No. 14.)

It has already been shown how necessary it is that the ship's magnetism, causing the deviation on east and west, should be resolved into its constituent parts, and each compensated by the means suitable to it; but to impress it more vividly on the mind, just consider what happens when this has been neglected.

Diagram N° 14:
SWISS HEAD NORTH MAGNETIC.



Take the case of a southern-going vessel, having, say, 5 points natural deviation on east, 3 of which are due to vertical iron. The adjuster, having no time given him to sift the matter, compensates all 5 points, in happy-go-lucky fashion, by means of *permanent steel magnets*, and so the compass is rendered correct *for the time being*. But as the vessel goes south the vertical iron loses its power over the compass, and on the magnetic equator exerts none whatever; the steel magnet, on the contrary, is as strong as before, and having now all its own way—the vertical iron no longer counteracting it—causes an error of three points. By the time the vessel has got off Cape Horn, vertical iron has *again* become strongly magnetic, *but now with reversed poles, so that it pulls in the same direction as the steel magnet, and both acting together, cause 6 points of deviation*. Not only is this large error a trouble in itself, *but the directive force of the needle is so reduced as to make the compass sluggish, and almost worthless to steer by*.

Enough has been said to convince any one that *reliable* compass adjustment is beset with difficulties, and cannot be lightly undertaken. What dependence, then, can be placed on the hurried performance which is daily witnessed in some of our largest ports, when a lot of magnets are slapped down as the vessel leaves the dock gates, and a deviation card handed to the captain worth little more than the paper it is written on? This, however, is seldom or never the adjuster's fault.

The ports of Callao, Bahia, Calabar, Aden, Madras, Colombo, and many others, are practically on the magnetic equator, and ships lie at anchor in them for weeks, during which their captains might perfect the subpermanent and quadrantal portion of the adjustment; and be prepared to complete it, as already explained, on return to high latitudes.

HEELING ERROR.

The heeling co-efficient.—It is the error on the north or south point *by compass*, caused by *one* degree of heel, and is found by dividing the difference between the deviation, ship upright and ship heeling, by the number of degrees of heel.

For example, given the deviation on north, ship upright, equal to -21° ; when heeling 12° to starboard, equal to -3° ; this is equivalent to a *plus* change of 18° , which, divided by 12° of heel, gives $+1.5^{\circ}$ as the *heeling co-efficient* for each degree of heel to starboard. From this it will be seen that the heeling error is *directly proportional* to the amount of heel. Now, when the heeling error is given for any other than the north or south points, it is easily reduced to these by simply dividing it by the natural cosine of the number of points from north or south, then divide the result by the inclination to starboard or port, as the case may be, and you have the *heeling co-efficient* as before. For example, the heeling error on W. N. W., with 16° of heel to port, is -9.19° ; divide this by .383 (the natural cosine of 6 points) and you get 24° ; divide this by the heel (16°), and again we have the *heeling co-efficient*.

